UNIVERSITY OF OULU

FACULTY OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING
DEGREE PROGRAMME IN WIRELESS COMMUNICATIONS ENGINEERING

MASTER'S THESIS

INFRASTRUCTURE BASED COMMUNICATION ARCHITECTURE TO FACILITATE AUTONOMOUS DRIVING AND COMMUNICATIONS

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September 2019

Rajapakshalage D. (2019) Infrastructure based communication architecture to facilitate autonomous driving and communications. University of Oulu, Faculty of Information Technology and Electrical Engineering, Degree Programme in Wireless Communications Engineering, 49 p.

ABSTRACT

The traditional autonomous vehicle (AV) architecture places a heavy burden on graphics processing units of the vehicle due to heavy signal processing requirements. Ultimately this results in performance degradation in AVs. This is mainly due to advanced sensors, which enable the vision for AVs, like Light Detection and Ranging (LiDAR), radars and cameras. In most of the AV models accepted by many leading automobile companies, LiDAR plays a significant role. It generates a high definition (HD) point cloud of the surroundings to obtain a precise map. AV makes decisions based on that by processing Terabyte (Tb) scale data within the AV. Still, vehicle-mounted LiDARs are not capable of providing information beyond a human driver's vision.

To provide a solution for the above-mentioned drawbacks of the traditional AVs, we propose an infrastructure based communication architecture to facilitate autonomous driving and communications. A set of coordinated LiDAR modules with integrated transceivers, which are mounted at an elevation with a bird's eye view, can provide a much larger field of vision (FoV). Decisions are taken from a centralized body. We prove the technical feasibility of the system from sensing and communication point of view. The proposed architecture can play a supportive role with traditional AV architectures and it can be applied to many cases such as to automate harbours and factory floors.

In the second part of the thesis, we address a resource allocation problem with ultra-reliable and low latency communication (URLLC) for a factory floor. We have analytically proven the capability of the proposed system to establish a reliable (packet error probability less than 10^{-5}) and low latency (less than 1 ms transmission delay) links with sufficient throughput (kilobit scale) using a convex optimization problem. Latency, throughput and reliability variations are studied under the short packet transmission of the proposed system.

Keywords: Autonomous driving, Global perception, Centralized AI, LiDAR, Cameras, Verifiable Architecture, V2X, 5G, Resource allocation, URLLC, Convex optimization, Short packet transmission.

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FOREWORD

This thesis is related to the Master's degree program in wireless communication engineering, University of Oulu, Finland. The thesis contains research undertaken at Centre for Wireless Communications (CWC) and work has been financially supported in parts by High5, MOSSAF and 6Genesis (6G) Flagship (grant 318927) projects.

First of all, I would like to express my gratitude to Academy Prof. Matti Latva-aho for providing me the opportunity to join the Radio Access Technologies (RAT) group in CWC. I am so grateful to my supervisor and mentor, Prof. Nandana Rajatheva for the guidance he provided me even before the Master's studies, for the opportunities he created and for the kind support he provided throughout my Master's studies. I am so thankful to Adj. Prof. Pekka Pirinen, the project manager and second examiner for the thesis, for his constructive comments and ideas. Also, my gratitude goes to Dr. Kari Kärkkäinen, Wireless Communication Engineering program director and all the lecturers of the University of Oulu for their support throughout the past academic year.

My gratitude goes to CWC colleagues and my friends for their kind support and time invested in me.

Rest of my gratitude goes to my family. Thank you very much for the sacrifices you have done as parents to raise me to heights from zero.

Oulu, 13th September, 2019

Dhanushka Nalin Jayaweera Rajapakshalage

LIST OF ABBREVIATIONS AND SYMBOLS

Acronyms

3GPP	3rd Generation Partnership Project
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
AI	Artificial Intelligence
AoI	Area of Interest
ASIL	Automotive Integrity Safety Level
AV	Autonomous Vehicle
ASIC	Application-Specific Integrated Circuit
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CSI	Channel State Information
DBW	Drive By Wire
DSRC	Dedicated Short Range Communication
EC	Edge Computing
FoF	Factories of Future
FoV	Field of Vision
GPS	Global positioning system
GPU	Graphics Processing Units
HD	High Definition
ITS	Intelligent Transportation System
LiDAR	Light Detection and Ranging
LOS	Line of Sight
LTE	Long-Term Evolution
M2M	Machine-to-Machine
MAC	Medium Access Control
MANET	Mobile Ad-hoc Network
MIMO	Multiple Inputs Multiple Outputs
OFDM	Orthogonal Frequency Division Multiplexing
rpm	revolutions per minute
SNR	Signal-to-Noise Ratio
Tb	Terabytes
TTI	Transmission Time Interval
UDN	Ultra Dense Network
URLLC	Ultra-Reliable Low-Latency Communication
USDOT	United State Department of Transportation
VANET	Vehicular Ad-hoc Network
V2D	Vehicle-to-Device
V2G	Vehicle-to-Grid
V2H	Vehicle-to-Home
V2I	Vehicle-to-Infrastructure
V2P	Vehicle-to-Pedestrian

V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
WAVE	Wireless Access for Vehicular Environments
WLAN	Wireless Local Area Network

Symbols

$\mathbb{M}$	Set of M messages
B	Bandwidth of the system
B_c	Coherence bandwidth
D	information bits or short packet size
D^0	MAC layer overhead
d	Distance between transmitter and receiver
d_0	Reference distance
d_{ELiD}	Processing delay of ELiD
d_{FA}	Frame alignment delay
d_Q	Queuing delay
d_{Tx}	Transmission delay
d_v	In-vehicle processing delay
E_{tot}	Total energy of the system
f	Frequency
h	Channel impulse response
h_i	Channel impulse response for i^{th} vehicle
K	Power attenuation for d_0 distance
L	Total latency of downlink
$\boldsymbol{M}$	Vector containing all m_is in system
M	Total block length,Total Number of channel uses or symbols
m	Block length, Number of channel uses or symbols
m_i	Block length, Number of channel uses or symbols for i^{th} vehicle
m_i^{lb}	Lower bound for m_i
m_i^{Ub}	Upper bound for m_i
m^0	Physical layer overhead
n	Number of vehicles or $\|V\|$
$\boldsymbol{P}$	Vector containing all p_is in system
P_i	Doppler spectrum
P_r	Received power
P_t	Transmit power
p_i	Transmission power allocated for i^{th} vehicle
R	Rate (information bits per complex symbol)
s	-(lower bound of error)
T_c	Coherence Time
T_{sx}	Delay accounted time towards x-direction
T_{sy}	Delay accounted time towards y-direction
t	time
t_{max}	Maximum transmission time
t_{Sym}	Symbol time

V	Set of vehicles
v	Channel dispersion
v_x	Velocity towards x-direction
v_y	Velocity towards y-direction
w_i	AWGN for i^{th} vehicle
x_i	Transmitted signal for i^{th} vehicle
y_i	Received signal for i^{th} vehicle
$\mathbb{Z}$	Set of Integers
α_i	Amplitude of the signal
β	Path loss exponent
$\delta(t)$	Impulse response at time t
$\boldsymbol{\epsilon}$	Vector containing all ϵ_is in system
ϵ	Decoder error probability
ϵ_i	Decoder error probability of i^{th} vehicle
γ	SNR
γ_i	SNR of i^{th} vehicle
ϕ	Path loss due to shadowing
$\boldsymbol{\sigma}$	Vector containing all σ_is in system
σ_i^2	Noise power of i^{th} vehicle
τ_i	Delay of the signal
τ_s	Delay spread

1 INTRODUCTION

Communication has become an essential component in the information era. As people search for information while most of the day to day activities, wired communication systems fail to deliver the required flexibility. The emergence of wireless communication technologies was able to make our lives easier. American Times Use Survey reported that a person spends 1.1 hours for driving on average per day [1]. This fact reflects the requirement of wireless communication towards vehicles not only to make driving easy and safe but also to deliver information for passengers. High dynamicity of the vehicular environment is a tremendous obstacle to accomplish this task. Vehicular communication standards were developed to address this issue. It is compulsory to deliver required information with high reliability and less latency for some safety-critical applications such as autonomous driving. Well known vehicular communication standards, such as Dedicated short-range communication and LTE-V, continuously try to achieve high reliability for sub-millisecond latency. The ultimate requirement is to deliver additional information to the vehicle, which can not be seen by the driver or captured by the sensors. Providing situational awareness data to vehicles by the road infrastructure is a trending topic where a lot of research is going on. AVs equipped with advance sensors to collect situational awareness data is another highly discussed topic worldwide. This work has combined two research directions to derive an infrastructure based communication architecture to facilitate autonomous driving in a city area or a factory floor.

1.1 Background and Motivation

AVs have become one of the most discussed topics on the internet due to comfort, which it can provide to driver and passengers. Already proposed AV systems collect necessary information by vehicle-mounted sensors and process the received sensor data within the vehicle. This results in a complicated vehicle system with many power-hungry components. Supercomputers, high capacity storage, advance cooling systems and more reliable shock-absorbing mechanisms are needed to achieve this massive task. In the meantime, a vehicle requires information from the road infrastructure and other vehicles to get a better view of the surroundings, because sensors would not able to provide vision beyond several meters ahead. Limited vision is the cause for most of the road accidents happened recently.

AV manufacturers research on data offloading capability to infrastructure to reduce in-vehicle processing. Existing vehicle communication standards were not able to meet AV industry requirements as they wish to offload sensor data to infrastructure. Multiple high throughput links with high reliability and low end to end latency need to be established, which will be challenging even with 5G.

Services that need high reliability and low latency will get special attention with the arrival of 5G. Even though URLLC does not guarantee high throughput, downlink capacity is sufficient for sending control information from the infrastructure to the vehicle. Emerging concepts like Edge Computing (EC) and Ultra-dense networks (UDN) will be able to facilitate autonomous driving a lot. A well planned infrastructure will able to take responsibility for vehicle navigation by using these technologies.

1.2 Contribution of the Thesis

In this work, we propose an infrastructure-based communication architecture to reduce individual in-vehicle signal processing significantly. A smart infrastructure system with a centralized decision-making unit, will provide the required information needed for autonomous driving. Furthermore, the system is capable of providing the information on several kilometres ahead, which is an added advantage compared to the traditional AV systems. The technical feasibility is proven by addressing the sensing and communication feasibility separately. The commercially available LiDAR and a recently announced LiDAR is used to analyze the sensing feasibility after the discussions, which we had with LiDAR manufacturers. A set of link-level simulations were carried out to prove the feasibility from the communication viewpoint using the Vienna link-level simulator. The proposed system requires many emerging technologies to realize communications, signal processing and sensing. Meantime it will open many more research directions. The system can be extended for use cases such as the automated factory floors and the automated harbours. Based on the work carried out for the thesis, the paper "Autonomous driving without a burden: View from outside with elevated LiDAR" has been published in Vehicular Technology Conference 2019 Spring.

Then we considered one use case, autonomous navigation in a factory floor. We have formulated an orthogonal resource allocation problem to minimize the maximum decoder error probability of the system to achieve a higher reliability. The problem is constrained with URLLC conditions. The analytical results prove the feasibility of the system.

1.3 Thesis Structure

This thesis consists of five chapters and the remaining chapters are organized as follows.

Chapter 2 presents the background and literature required to understand the thesis. Background and related work chapter has four sections where it first discusses about vehicular communication. First, it describes vehicle-2-everything (V2X) communication mainly concentrating on vehicle-2-vehicle (V2V) and vehicle-2-infrastructure (V2I) communication. Then, it describes vehicular communication standards such as Dedicated short range communication (DSRC) and LTE-V with their applications and a comparison. As the second section, it explains AV systems. Arrangement, technologies and drawbacks of the existing AV systems are discussed. In the next section, it briefly explains the main features of vehicular channels. It presents few channel characteristics, which lead to large scale-fading and small-scale fading in a general way. Finally, it presents related works that has already been carried out.

Chapter 3 presents a novel infrastructure-based communication architecture, which can facilitate autonomous driving. An overview of the architecture is presented along with an introduction to the problem. Then, technical feasibility of the proposed system is provided with from the sensing and communication system point of view. Next, a comparison is carried out between the traditional AV system and the proposed system. Further, this contains a few research problems, which need further attention.

Chapter 4 discusses one use case of the proposed system. Initially, this explains how short packet transmissions help to achieve low latency in communication. After that the system model is presented and then the resource allocation problem has been formulated with URLLC constraints. Simulation results and required explanations have been provided in the next section. Finally, the discussion of the results is presented.

Chapter 5 includes the summary of the thesis and the conclusion of the work.It ends by presenting the remaining work to be done in the future.

2 BACKGROUND AND LITERATURE

This section provides the relevant background information that is needed to understand the thesis. Road accidents and traffic congestion have become a primary issue for the transportation sector. Approximately 1.25 million people die due to road accidents annually, 3287 deaths on average per day [2]. Passengers have to waste a lot of time for transportation in peak traffic hours. In the meantime traffic congestion will directly contribute to air pollution. Road infrastructure and vehicles facilitated by technology would be able to drop down these figures eventually. Vehicular communication serves as a significant solution and a trend to improve road safety while reducing traffic congestion.

2.1 Vehicular Communication

Vehicular communication has become one of the latest additions to wireless communication systems. Vehicles moving on roads may be considered as communication nodes, and they should establish reliable communication links to share information among neighbouring vehicles/road infrastructure. There are two main categories in the vehicular communication, vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. Merging all types of communications related to vehicles (including V2V and V2I) are known as vehicle-to-everything (V2X) communication. Protocols such as IEEE 802.11p and standards like LTE-V have been developed to assist V2X communication. These topics been have addressed separately in this section. Figure 2.1 shows the main vehicular communication types.

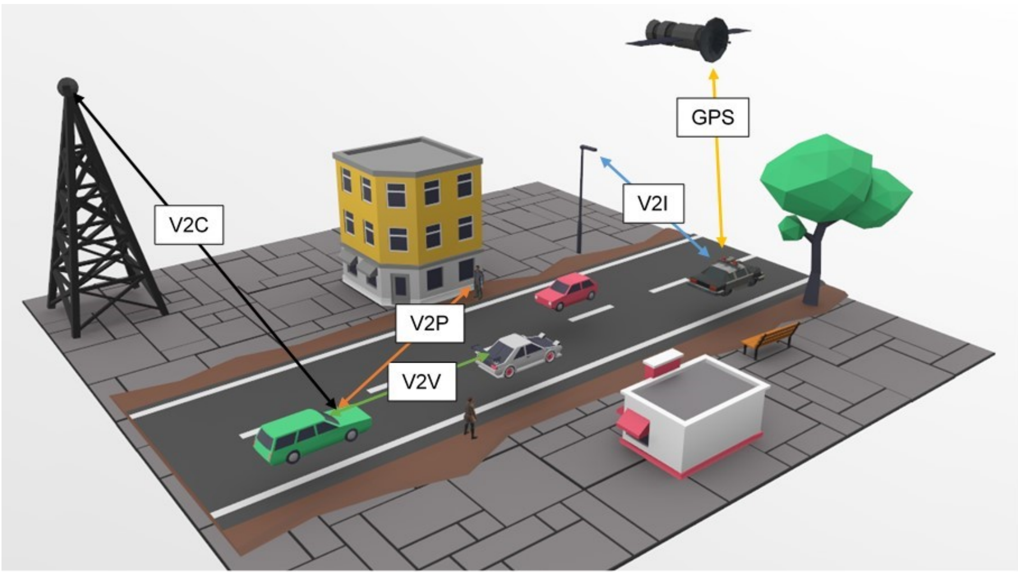

Figure 2.1. V2X communication types ([3] ©2019 IEEE).

Establishment of wireless communication links between two or more moving vehicles is known as V2V communication. The main objective of this communication is to prevent possible accidents by sharing information about the vehicle with neighbouring connected vehicles. Vehicles will share information on GPS position, speed, heading direction, acceleration, transmission state, brake status, steering wheel angle and path history among the other vehicles. Those are important to predict the environment for the next few seconds. Vehicular ad-hoc networks (VANETs) are special kind of Mobile ad-hoc networks (MANETs), which are very complicated due to high mobility. Vehicles share information in a single hop or multi-hop manner to flood the vehicular environment with safety messages. This technology helps to reduce the accidents caused by blind spots and unexpected behaviours of motor vehicles. V2V applications can be categorized as follows [4]:

- Safety related applications: Collision avoidance, cooperative driving and vehicle platooning, lane merging.
- Incident reporting: Data on incoming traffic, network or vehicle breakdown.
- Route Guidance: Shortest path to destination, Information on gas stations and parking slots.

V2I communication is the sharing of information from the road infrastructure to the vehicle and vice versa. Vehicles tend to communicate with road side infrastructure units (RSUs) to gather information on the surroundings. It can be a traffic light system, a lamp post or a road sign. V2X communication is reliable compared to V2V communication due to fixed RSUs. Generally, V2I links are bidirectional communication links as the V2V links.

V2X communication can be subdivided into vehicle-to-device (V2D), vehicle-to-pedestrian (V2P), vehicle-to-grid (V2G) and vehicle-to-home (V2H) including V2V and V2I communications. V2X refers to communication with any entity in the road infrastructure. According to the records, pedestrians, motorcyclists and cyclists are highly vulnerable to road accidents, and this is prominent in urban environments due to high road traffic intensity. The primary purpose of V2P and V2D communications is to share precise location information of pedestrians and cyclists with moving vehicles and vice versa. It is necessary to have an alerting system for pedestrians and cyclists to send information on traffic status for their safety [5].

2.1.1 Vehicular Communication Standards

This section discusses the vehicular communication technologies, which enable V2X communications. Dedicated short range communication (DSRC) and LTE-V are two leading communication standards in this field.

DSRC/Wireless Access for Vehicular Environments (WAVE) was introduced by the US department of transportation (USDOT) to support mobility and safety applications. They have proposed more than 57 application scenarios for connected vehicles and some of them are listed in the following Table 2.1 [6]. Listed applications show that most of the safety applications require a latency around 100 ms, which is nearly equivalent to the response time of a human driver. The underlying technology of DSRC is Wireless Local Area Network (WLAN) protocol IEEE802.11p, which is proposed by IEEE. In the US, authorities have allocated a 75 MHz band spectrum (5.850 GHz - 5.925 GHz) for DSRC purposes. This band consists of one control channel and six service channels [7]. Some of the channels are reserved for future actions. DSRC is a well-established technology among all due to extensive tests and research carried out so far. But, so far DSRC has not been able to address scalability issues as load increases.

Table 2.1. Safety applications and required latency

Application	Required latency
Precrash sensing	20 ms
Traffic signal violation warning	100 ms
Emergency electronic brake lights	100 ms
Cooperative forward collision warning	100 ms
Lane change warning	100 ms
Stop sign movement assistance	100 ms
Curve speed warning	1 s

LTE-V mainly focuses on using existing cellular communication infrastructure to establish reliable communication with moving vehicles. Cellular-V2X and LTE-V2X are two other common terms that refer to LTE-V. The first version of release 14 announced by the Third Generation Partnership Project (3GPP) included the V2X support for the first time [8]. The link budget has been improved by LTE-V physical layer compared to DSRC. LTE-V includes two radio interfaces, namely Uu and PC5. Uu or cellular interface is for V2X communication and PC5 is for V2V communication based on a direct LTE sidelink. In release 12, 3GPP introduced two modes of operation as mode 1 and mode 2. Later in release 14, they introduced two additional modes as mode 3 and mode 4. Some important features of these modes are shown in Table 2.2 [9].

Table 2.2. Operation modes of LTE-V

Mode	Feature
Mode 1 and 2	Designed to save the battery life of the mobile devices at a cost of latency. Not recommended for vehicular applications.
Mode 3	Radio resources used for V2V communication are managed by cellular networks.
Mode 4	Vehicles autonomously select radio resources, Can operate without a cellular coverage.

From the physical layer perspective, LTE-V supports 10 MHz and 20 MHz channels. Each channel is divided into sub-frames and sub-channels as in LTE[9]. A comparison between DSRC and LTE-V communication technologies is shown in Table 2.3[10].

Table 2.3. Comparison of features in DSRC and LTE-V

Feature	DSRC	LTE-V
Channel width	10 MHz	Up to 100 MHz
Frequency Band	5.86-5.92 GHz	0.45-4.99 GHz
Bit rate	3-27 Mb/s	Up to 1 Gb/s
Range	Up to 1 km	Up to 30 km
Capacity	Medium	Very high
Coverage	Intermittent	Ubiquitous
Mobility support	Medium	Very high
Market penetration	Low	Potentially high

Even though both technologies have a common aim to achieve real-time safety communication between a vehicle and the infrastructure, both have their pros and cons. DSRC is mostly preferred for safety applications due to high reliability and low latency but not preferred for applications, which need high data rates. DSRC is not yet able to address scalability issues. On the other hand, LTE-V can achieve higher data rates that can even support video streaming. LTE-V mostly preferred for non-safety critical applications due to its high latency. Availability of the infrastructure is a key advantage in LTE-V. In order to make ITS a realistic concept, both standards play a vital role and it is not expected that DSRC or LTE-V can handle all the required connections as a single technology [11].

2.2 Autonomous Vehicle System

Autonomous driving is not a new idea, the vision of AVs emerged in the mid-20th century. In recent two decades, it drew the attention of industry and academia due to the advancement of the technologies like sensing, signal processing and communications [12]. Supercomputing and cloud computing capabilities along with artificial intelligence, became key enabling technologies for self-driving vehicles [13], [14]. Most of the leading automobile manufacturers put a lot of resources and effort on research and development. Automobile manufacturers such as General Motors [15], Ford and Tesla[16] have plans for the commercial AVs while transportation services-oriented companies like Uber test their AVs to remove the human interaction from offered services [17]. Driver-assisted automated systems have already been installed in 15% of the vehicles by 2015 and it will increase up to 50% to 60% by 2020 according to the expectations[18]. Experts in the

AV industry predicted the first appearance of a fully AV would take place in 2018 [19]. However, they are far behind the predictions by now. The ultimate expectation is to achieve full autonomy. Different levels of automation are described in Figure 2.2 [12].

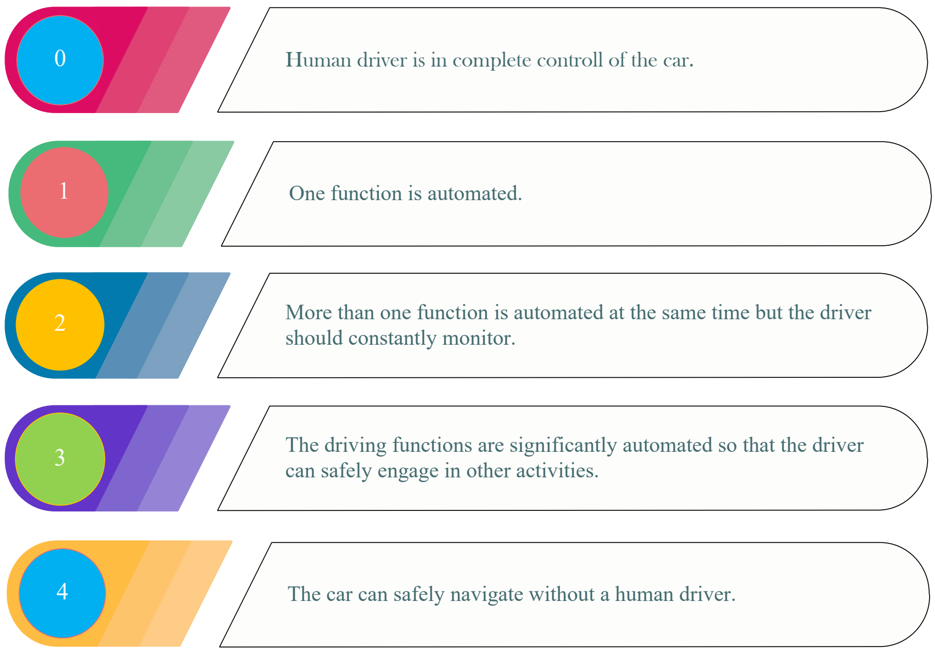

Figure 2.2. Different levels of automation.

AVs became more popular as they can release humans from driving and time allocated for driving can be utilized for other meaningful work. At the same time it will lead to fewer road accidents due to less human interaction and the transportation will be more enjoyable compared to driving a traditional vehicle.

2.2.1 Current AV System Architecture

Even though there are arguments for the best AV system design [20], Figure 2.3 shows the widely accepted AV system design [21].

Advanced sensing technologies play a vital role to enable the vision for autonomous driving. LiDAR sensor, which is fixed on top of the vehicle (in most of the systems), generates a high-resolution point cloud of the surroundings for the map generation. Spinning capability of the LiDAR helps to scan the environment for multiple times within a second and collect data from all the directions. High-resolution camera modules capture the data required for object recognition such as road signs, fog lines and colour lights. It is not an easy task to remove the infrastructure that provides information visually as all vehicles on the roadways translate to AVs. Camera modules are required to capture such data that can not be sensed by other sensors. Radar, Ultrasonic and infrared sensors measure the distances to the nearby obstacles and help to improve the accuracy of the final map. Those sensors help to minimize the blind spots around the vehicle, which are not visible to the rotating LiDAR.

A central processing unit will collect sensor data, which is usually placed in the back of the vehicle inside a cabin with a special cooling system. The translation of the received raw sensor data to the meaningful information is carried out by the GPUs. Periodical information or event-driven control information is passed to the driver as an alert or via the driver-by-wire (DBW) system as an electrical signal. Most of the modern vehicles are DBW enabled. It performs the functionalities by electrical signals, which were earlier done by mechanical systems [22].

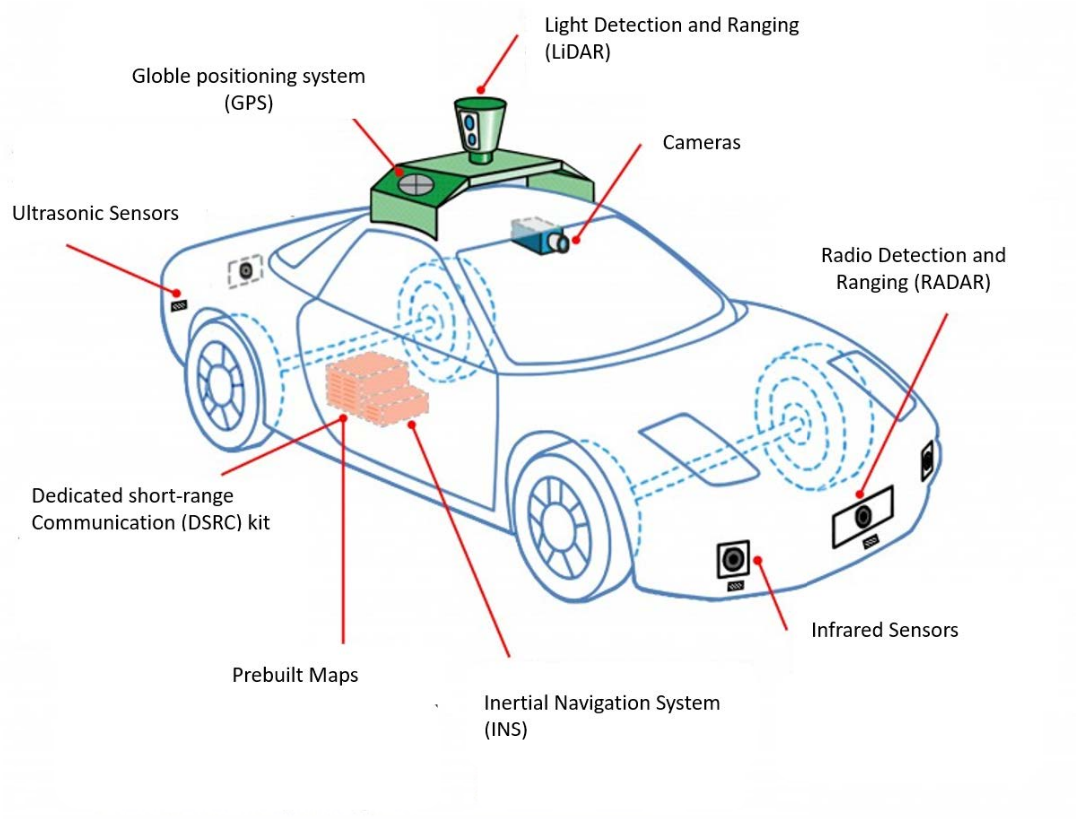

Figure 2.3. AV system.

There are many design constraints in the existing AV systems [23]. The vehicle should respond to incoming situations within a short time to avoid accidents. Frame rates of the generated maps and processing latency determine the response time of the AV system. Generally, the fastest possible reaction time of a human driver is in the range of 100 to 150 ms [23]. To replace the human driver, at least the response time should be less than 100ms. It requires a powerful processing system to achieve the required latency, approximately 40 times faster than a standard computer. It is a common trend to store offline maps of navigating areas in the system, because it is infeasible to download them from a remote storage (e.g., cloud). Prior maps are useful to get an idea about the environment even without internet connectivity. To store a high-resolution map, AV needs a TB scale storage. For an example the entire map of the United States is about 41 TB. Ultimately, these supercomputers and storage systems occupy a considerable space in the vehicle. The heat generated from these systems can diffuse to the passenger cabin. It is reported that the cabin temperature may go up to 105^0C in the absence of a reliable cooling mechanism, which is another addition to power-hungry components. All these components collaboratively reduce the efficiency of the system by 11.5% compared to the traditional motor vehicles. Other than that all the additional systems should withstand high impacts. Shock absorbing mechanisms should be able to resist impacts to secure the system in case of an accident[23].

As a commercial product, the AV system should be able to get customer interest. We have pointed out some issues that are needed to be addressed before announcing this as a commercially available AV.

- Market price of the AV - As the LiDAR cost is nearly 8000 USD, the market price will be very high. If AV is not affordable for the majority of vehicle users, this will delay the journey towards ITS.
- Shape of the AV - All the sensor modules, such as mounted LiDARs, add an abnormal shape to the vehicle.
- Performance degradation compared to traditional motor vehicles.
- Reduction of space utilization.

Ongoing research and development works should be able to provide a solution for the issues mentioned above to make a return on investments.

2.3 Vehicular Channels

The most fundamental factor differentiating vehicular communication from other traditional wireless communication systems is their channel propagation characteristics. In a highly dynamic environment, channel characteristics vary rapidly. Mathematical modelling of channels should account all those temporal variabilities to generate a more realistic system model. In this section, we have presented some wireless channel characteristics.

Transmitted signals from the transmitter propagate to the receiver through different paths. All received components with different delays may have different amplitudes and phases compared to each other. These multipath components may add constructively or destructively in the receiver. The effect is known as the fading. Fading can be separated into two types as large-scale fading and small-scale fading. Path loss and shadowing are two main contributors to large-scale fading. Path loss happens due to the absorption, scattering, reflection of the signal while propagating and shadowing due to obstacles on the propagation path [24]. Expected power loss (in dB) at the receiver due to both these effects is

$$P_t - P_r = K + 10\beta log_{10}(d/d_0) + \phi \tag{1}$$

where P_t and P_r denote the transmitted power and received power respectively while K represent the power attenuation for a d_0 reference distance. β is a constant depending on the propagation medium, which is known as path loss exponent. ϕ denote the power loss due to shadowing, which can be modelled by a Gaussian distribution. Small-scale fading happens due to the time-varying multipath components. The channel impulse response of a such can be modelled as

$$h(\tau, t) = \sum_i \alpha_i(t)\delta(\tau - \tau_i) \tag{2}$$

where $\alpha_i(t)$ and τ_i represent the time varying amplitude and delay of the i^{th} multipath component.

The power delay profile of the channel is another characteristic, which describes the frequency selectivity of the channel. The delay spread (τ_s) of the channel can be characterized as

$$\tau_s = \sqrt{\frac{\sum_i E[|\alpha_i|^2](\tau_i - \tau_a)}{\sum_i E[|\alpha_i|^2]}} \tag{3}$$

where

$$\tau_a = \frac{\sum_i E[|\alpha_i|^2]\tau_i}{\sum_i E[|\alpha_i|^2]} \tag{4}$$

The frequency band at which the channel response is roughly uniform is known as the coherence bandwidth (B_c) of the channel. As B_c of the system is inversely proportional to τ_s, it will significantly affect the frequency selectivity of the channel. Doppler spread characterize the time variations of the vehicular channel. Doppler spectrum can be defined as

$$P_i(f) = \int_{-\infty}^{+\infty} E[\alpha_i(t+\tau)^*\alpha_i(t)]exp(-j2\pi f\tau)df \tag{5}$$

The channel coherence time (T_c) is inversely proportional to the Doppler spectrum and it describes the time period where the channel impulse response remains nearly constant. As the mobility increases in a wireless communication system, the Doppler spectrum increases. Ultimately it results in a short coherence time.

2.4 Related Works

A concept on special traffic corridors is presented in [22] also known as Special Infrastructure Enabled Traffic Corridors. They describe the distribution of responsibilities and liabilities of current AVs and non-AVs and propose an infrastructure-based system, which can share the responsibilities and liabilities. They assess the "Blame" for a component after distributing the responsibilities. They show that this approach will able to accelerate the deployment of AVs. The ability of a modified infrastructure system to deliver a low cost in-vehicle technology is presented in [25]. The capability of the infrastructure mounted sensors in an intersection with a bird's eye view is discussed in [13]. Unikie Oy, a Finland based company has merged two LiDARs to improve the accuracy of the LiDAR point clouds. The same technology can be applied to the proposed system [26]. The role that the infrastructure based sensors can play and advantages of utilizing such sensors to yield greater safety of operation for the AVs have been discussed in [27].

3 THE PROPOSED ARCHITECTURE : ELEVATED LIDAR SYSTEM (ELID)

Signal processing and data storing burden is a significant problem in the AV industry. They prefer in-vehicle processing due to latency constraints but can not offload the collected data since available V2I standards are unable to handle massive data chunks. According to the discussions with AV experts, they stated that the support of wireless communication standards to offload data to the infrastructure is not up to the expected level of AV industry. Automobile manufacturers' requirements are much higher than the developed standards and ongoing vehicular network-related research. Now they are waiting for 5G. The next puzzle is whether it will able to establish gigabit range V2I links to offload data to the road infrastructure. In this chapter, we propose a novel AV architecture, which can reduce the burden towards the V2I link.

If we recall the initial stage of the racing car games, most of the games were designed with a bird's eye view. It is easier to handle the car because the camera angle gives an overall idea about the current environment. Playing the game was effortless with fewer predictions about the next moment. To be more realistic and to improve the user experience, designers brought the camera angle much closer to the vehicle, which is more similar to the driver's angle. Controlling became challenging compared to the early stage games due to the absence of informative data to the player. Current AVs collect the situation awareness data from the same angle for the map generation. It is similar to the driver's range of vision with a bit of the elevation. Even though multiple cameras contribute to the map generation, it will not enough to remove all blind spots. The current AV system is like replacing the human driver by a set of sensors which have the same capabilities. The Field of Vision (FoV) is nearly equal in both cases. The limited FoV will not help to reduce unpredictable accidents, and it is very unlikely to improve reliability. Vehicles should have a third eye to monitor the environment from a different angle, which can improve the reliability of the autonomous driving as in early-stage video car games (Figure 3.1). Elevated LiDAR (ELiD) system is proposed based on this idea.

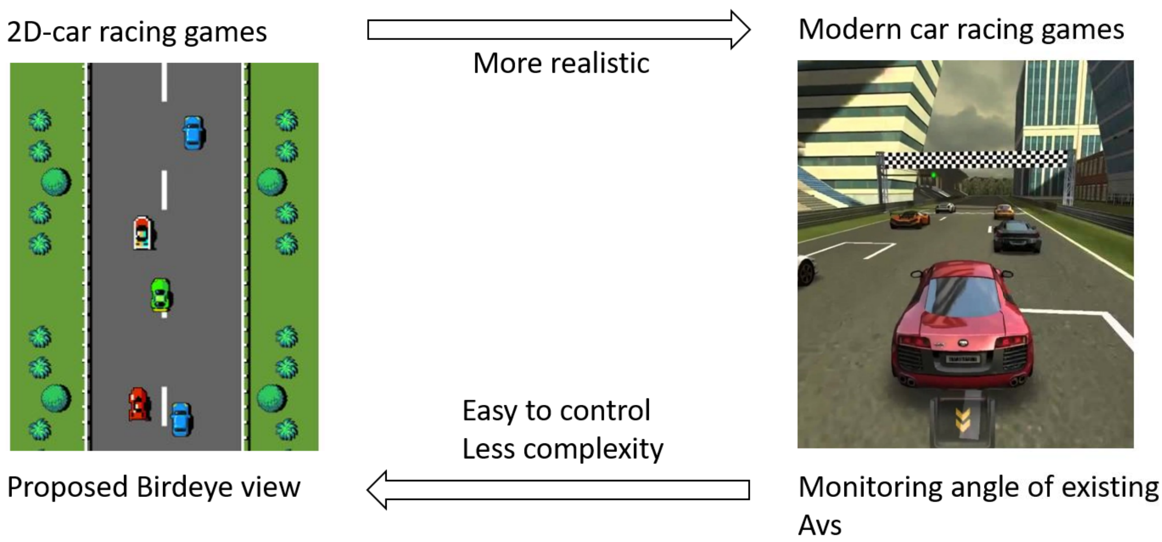

Figure 3.1. Evolution of racing games vs. the proposed solution.

The ELiD system is an infrastructure based sensing system that communicates with moving vehicles. According to Chapter 2 this can be considered as an RSU with a bird's eye view.

3.1 Architecture Overview

The proposed system should be equipped with a high-resolution sensor to collect situation awareness data and URLLC capable communication module to establish V2I links as shown in Figure 3.2. LiDAR, high-resolution cameras and radar are possible sensing technologies to be used for the ELiD system. Table 3.1 presents specifications associated with each technology.

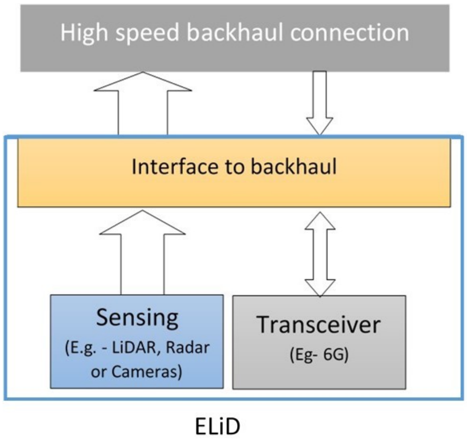

Figure 3.2. Components of the ELiD.

Table 3.1. Specifications of different sensing technologies

Sensing technology	Range	Accuracy
LiDAR [28] (Ouster OS1)	120m (depends on reflectivity of the object)	3cm (average)
Radar (Automotive) [29]	Will differ according to the application.(e.g., 1.5m - 250m)	Range accuracy $< 2.5\%$
High resolution camera	Between 91 and 250 meters	Can identify trained objects within the range

To consider a technology as a suitable candidate for infrastructure-based sensing, it should ensure accurate identification of objects. A high-resolution output is required even for a long range (nearly 150m). In the radar technology, there is a trade-off between the range and the resolution [29]. Accuracy of the cameras is highly dependent on the intensity of light and in the night time, it is very difficult to rely on such a system. By considering all specifications and literature, LiDAR is the best candidate over the other two sensing technologies to generate a map [30] in this system due to its high precision. The sensing section of the ELiD system is made up of two LiDAR sensors (details are provided in Section 3.2) that are inclined to each other. The two LiDAR sensors are combined in the ELiD and mounted in an elevated position in the road infrastructure to create a bird's eye view. ELiD can generate a HD point cloud over a responsible road section. A set of ELiD modules, which are fixed along a road, can collectively sense and transmit the collected data to a central location (CL) through a high-speed backhaul connection. CL is responsible for generating a global map of the area using the received point clouds. Then it will make decisions (e.g., collision detection, collision avoidance, path planning) based on the generated map. The required decisions will be sent back to the corresponding ELiDs and then to the vehicles as a downlink communication.

ELiD is centred to the road and mounted on a high elevation. Two stationary LiDAR sensors collaboratively cover their region up to the maximum accurate distance. The transceiver module of the ELiD receives other supportive sensor data from moving vehicles and transmits decisions and commands required for the navigation of vehicles. CL and ELiDs are connected using a high-speed fibre backbone. ELiD is the crucial component of the system to monitor the environment up to a few centimetre precision and is responsible for establishing a reliable vehicle to infrastructure (V2I) communication with low latency.

A high-speed backhaul connection is required to transfer point cloud data from the ELiDs to the CL. Optical fibre is the best option that can be found in urban areas [31]. The length of the fibre connection can be defined based on the latency constraints. Data processing and storing should be done in a highly secured environment in the CL. All the actions should be reported to a vehicle within 100 ms after sensing to guarantee safety. Algorithms, which need to perform data fusion and map generation, object recognition and detection, and path planning, are running on extremely powerful computers in the CL. Real-time maps can be generated from the stored data for multiple applications such as traffic predictions with better precision than in the existing applications.

3.2 Technical Feasibility of the ELiD System

This section presents the feasibility of the proposed system from sensing and communication viewpoints.

3.2.1 Sensing Feasibility

Sensing feasibility can be proven by commercially available (and announced) sensors. In the AV industry, LiDARs are used to map the surroundings by capturing data from all directions. So, rotation is the most critical factor in most of the commercial LiDARs. Most of the leading LiDAR manufacturers put more focus on vehicle mounted LiDARs, which are rotating at 300 to 900 rpm due to the existing AV architecture [32]. These rotating LiDARs are very expensive due to their actuators. For the ELiD system, we use Velarray LiDAR sensor, which is a solid-state LiDAR announced by well known Velodyne LiDAR (Figure 3.3) with following specifications [32],

- 120^0 horizontal field-of-view

- 35^0 vertical field-of-view
- 200 m range for even low reflective objects
- Small form factor (125mm X 50mm X 55mm).

Velarray is a cost effective and high performing LiDAR, which has an estimated price in the hundreds of dollars in the mass production. It has an Automotive integrity safety level (ASIL) B rating to guarantee its applicability. They have produced this to ensure safe operations in level 4 and level 5 AVs [32].

Figure 3.3. Field of View Measurement [33].

Our main objective is to use Velarray LiDARs to cover a road section with the required accuracy from a bird's eye view. We assume a highway in the United States for calculations with the assumptions shown in Table 3.2.

Table 3.2. Assumptions ([3] ©2019 IEEE)

Average lane width in US (City)	3.7m
Number of lanes in the road	Four
Safety margin from the outer most lane	3m

We calculated the elevation of the ELiD system by mapping the vertical FoV to the width of four lanes, as shown in Figure 3.4. Horizontal FoV will maximize the coverage distance of the ELiD along the road as in Figure 3.5. As mentioned earlier, we use two inclined stationary LiDAR sensors in the ELiD system with a 120^0 horizontal FoV. Inclination makes it possible to extend the horizontal FoV. Two LiDARs sense the responsible road section from both directions. With the same set of assumptions as in Table 3.2, we carried out the same calculations for a commercially available OS-1 (16-64) rotating LiDAR [28]. A comparison of the results is shown in Table 3.3.

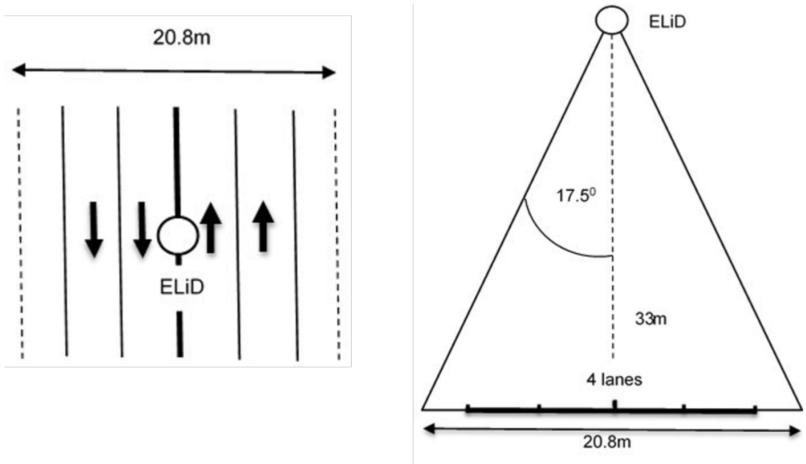

Figure 3.4. Top and side view ([3] ©2019 IEEE).

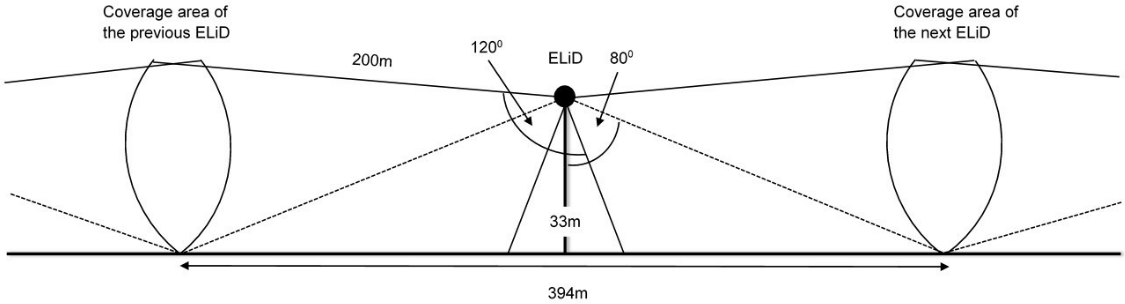

Figure 3.5. ELiD range ([3] ©2019 IEEE).

Table 3.3. A summary of the calculations ([3] ©2019 IEEE)

LiDAR	Velarray	OS-1(16 or 64)
Elevation of the ELiD	nearly 33 m	36.75 m
Number of LiDAR sensors per ELiD	two	one
Maximum coverage distance	nearly 394 m	222.5 m
LiDAR density	>5 units/km	<5 units/km

We selected Velarray LiDAR for further investigations. This is mainly due to its cost-effectiveness for this system. According to the calculations, ELiD should be mounted on a height of 33m from the ground level. It is a considerable height compared to the normal RSUs that we discuss in the literature. In an urban area, we can realize this using skyscrapers. The proposed system (Figure 3.6) is more suitable to an urban area due to the availability of the infrastructure. Normally urban areas are covered with optical fibre networks. Collected point clouds can be sent to the CL using those existing links. It is not necessary to deploy a dedicated fibre network for this operation, but the only additional requirement is to link the backhaul to the ELiDs. Optical fibre carries data close to speed of light i.e., 203 to 205 km within a millisecond [31]. Based on the amount of ELiD modules per unit distance, we carried out fibre backhaul related calculations. Those results are summarized in Table 3.4.

Table 3.4. Backhaul related results ([3] ©2019 IEEE)

Maximum fibre length to the CL	100 km
Propagation delay	1 ms
Required data rate	50 Gbps

The same idea can be extended to give coverage to rural areas by reducing the precision of the ELiD system. The precision of the map is not a crucial factor for a rural area compared to an urban area. Vehicle density is less and installation of the ELiD system according to the previous specifications will not give a good return on investment. In the system, we can increase the elevation at the cost of precision, which will result in decreased LiDAR density. According to this, we will be able to minimize the cost because LiDAR is the most expensive component among all. Right-of-way concept states about the high-speed fibre backhaul in rural areas [34]. Obtaining greater heights may be difficult due to the lack of tall buildings. It can be sorted-out using a low-cost approach such as a balloon system or using a low-cost civil construction method.

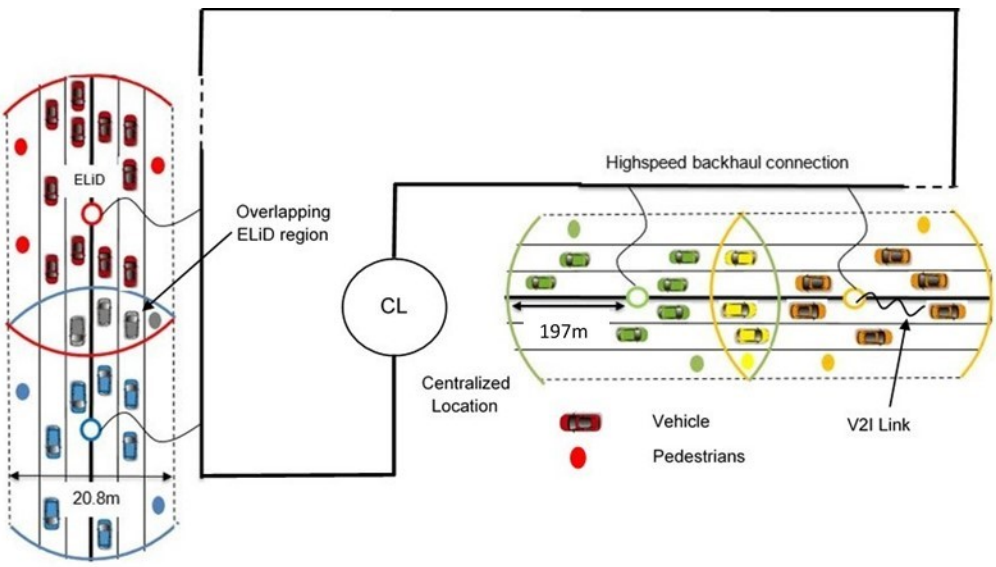

Figure 3.6. System Overview.

As we mentioned earlier, CL is responsible for fusing data collected by all ELiD modules. The Company called Unikie has merged two LiDARs in real-time to improve the accuracy of the data [26]. Such technology could be extended to improve the reliability of the ELiD and to generate a coordinated view.

With a high-resolution global map, the CL would be able to detect objects near to a vehicle in the same manner as in the existing systems. Due to the stationarity, ELiDs are well aware of the distance between ELiD and the road. Algorithms running in the CL (e.g., AI/Machine learning) could be able to detect moving speeds of vehicles. Those data can be validated using the data received by each vehicle. 'Area of Interest' (AoI) can be defined per vehicle based on the speed as shown in Figure 3.7 (length of AoI is proportional to the instantaneous speed). v_x and v_y are velocity components towards the moving direction and sideways, respectively, while T_{sx} and T_{sy} are total delays accounted and estimated time values, which guarantee a safe braking distance. For a vehicle, the object detection algorithms are interested only on the objects which reach the AoI. Then CL will send an event-driven message to the onboard systems to apply breaks immediately according to the predicted motion of the obstacle.

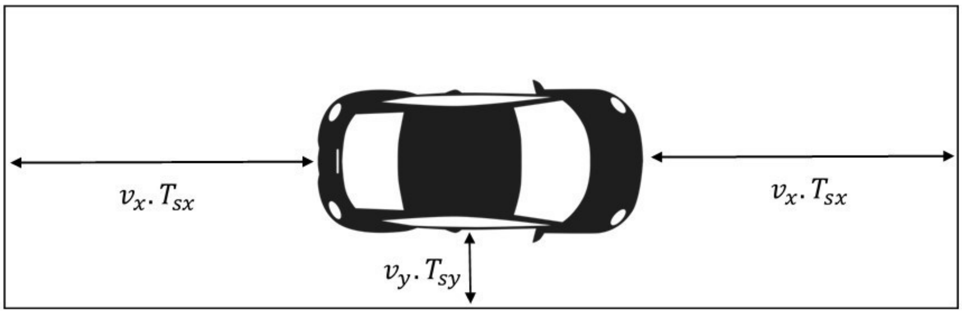

Figure 3.7. Area of interest.

3.2.2 Feasibility from Communication System Viewpoint

As we discussed in Chapter 2, all leading protocols like LTE-V and DSRC should establish and maintain multiple high capacity links with the required quality to offload collected data from vehicles. Before focusing on the communication system, we would like to analyse the reduction of burden towards the communication link by the proposed system compared to the existing AV architecture. Table 3.5 summarises the expected performance (EP) of the existing V2I protocols, the requirements for current AVs (RCAVs) to offload the collected data and the requirements for the proposed architecture (RPA).

Table 3.5. Comparison of link requirements ([3] ©2019 IEEE)

	Throughput	Latency	Link
EP	5 Mbps	2-10 ms	Uplink and Downlink
RCAVs	>250 Mbps	round trip <100 ms	Uplink and Downlink
RPA	100's of kbps	round trip <100 ms	only Downlink

Table 3.5 depicts that the proposed system has significantly fewer and lesser stringent requirements from the wireless communication point of view. ELiD has a less round trip delay (time between transmitter time of captured data and received time of control data) since it collects situational awareness data from the infrastructure. The required throughput is very much less compared to the existing AVs because it needs only the control data (commands required for navigation) back to the vehicle. In this case, we have

only considered the downlink communication. The ELiD system can receive supportive data such as speed, location and direction (but not the sensor data) from the vehicles to make an accurate decision based on what is received. Although it requires a bidirectional link, uplink capacity should be the same as the downlink capacity.

5G mobility is still an open research area where many researchers focus on. Since the proposed system has a track of positions of each vehicle, this can be an ideal fit for 5G to revolutionize autonomous driving. Line of sight (LOS) guaranteed small cell size and importance of the downlink bring focus towards ultra-dense networks (UDN). UDN guarantees a highly reliable and high capacity downlink with low latency. V2I specifications with 5G radio interface have been tested by a set of researchers from Huawei, Germany [35]. LOS communication was their primary objective, and they state that UDN can provide required positioning, latency and reliability rather than depending on MIMO. They have implemented a testbed and tested downlink using two cars. Obtained results are summarized below:

- Reliability of the V2I link is greater than 99.999%
- Maximum speed up to 170 km/h
- Average latency of V2I is nearly 0.7 ms.

Above results verify the feasibility of the proposed system. Achieving high reliability for a low latency even at higher speeds makes it possible to deploy this system on highways with improved processing capabilities. The performance of the testbed may degrade as the number of vehicles increases. Those problems can be sorted out by reducing cell size. As the communication section of the ELiD module works as a UDN network, it is a best fit to the upcoming 5G echo system.

As we discussed earlier, CL is the place responsible for storing and processing data. It can equate this to the brain of the system. Security of the CL is a primary concern and the system should not lead to a single point of failure. Having a disaster recovery CL (DRCL) will minimize the single point of failure. Still, latency will be high during the transition between CL and DRCL. To minimize the single point of failure and to reduce the latency, a distributed architecture is a better option. We can shift processing capabilities towards the ELiDs, which will reduce the end to end delay. It will help to minimize the security vulnerabilities of the system. Edge computing (EC) principles can be used for this purpose (Figure 3.8), and it will reduce the latency as well as the bandwidth in the network.

EC can be performed for groups of ELiDs to expand the responsible region of CL while meeting latency constraints. This assists to improve the scalability of the system. The EC server is responsible for processing data received by a set of ELiDs and to generate required control information and safety messages for vehicles. EC can be used to separate the systems geographically or according to the traffic density. Processing capabilities and security should be up to the required levels. A set of EC servers reports to the CL. The CL is responsible for global actions like online map generation for third-party applications. With the support of EC, many constraints in the proposed system can be relaxed.

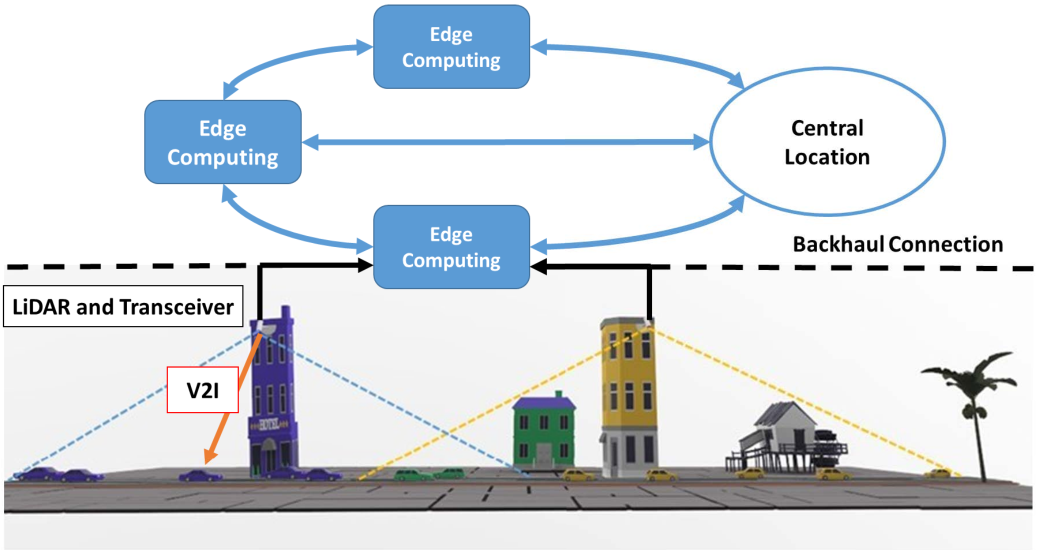

Figure 3.8. EC integrated ELiD system.

A set of link-level simulations carried out to evaluate the performance of the downlink communication in a small cell with the LTE technology, using Vienna link-level simulator [36]. A small cell is considered with a radius of 200 m and a traffic density with ten vehicles per ELiD, which corresponds to 25 vehicles per km with a speed of 72 km/h each. All the users are cell edge users so that better performance for other users can be expected. A 5 MHz bandwidth is allocated to a cell, and only downlink is simulated. Throughputs and bit error rates (BERs) are evaluated against the signal to noise ratio (SNR). Since all users are treated equally, resulting graphs for user one are shown in Figures 3.9 and 3.10.

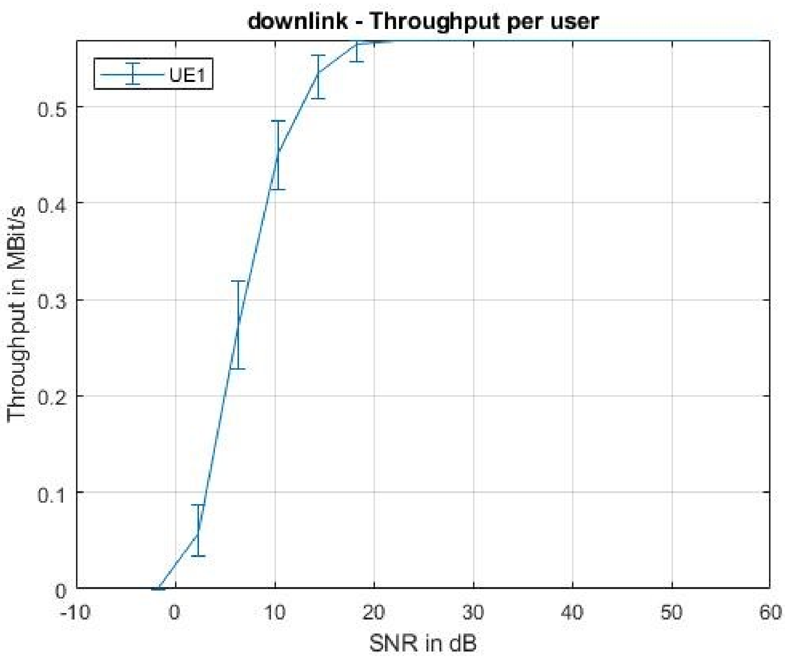

Figure 3.9. Throughput vs. SNR.

According to Figure 3.9, the user experiences throughput higher than 100 kbps when SNR is greater than 3 dB. As the SNR increases, throughput will increase, and the user will experience the maximum throughput of 575 kbps approximately beyond 20 dB. As in Table 3.5, our expectation was 100's of kbps and results are well within the requirement.

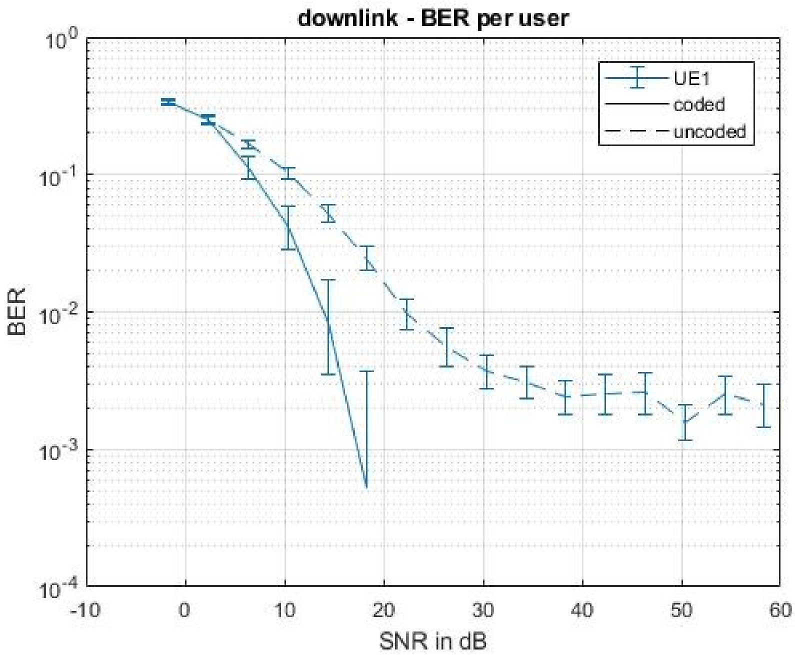

Figure 3.10. BER vs. SNR.

According to Figure 3.10, BER of the coded and uncoded communication will reduce as SNR increases. The coded BER will be nearly 10^{-3} as the SNR reaches 18 dB. The expected reliability is not achieved through the preliminary results, and this is taken into consideration in Chapter 4. Simulation parameters of the setup are shown in Table 3.6.

3.3 Comparison of the ELiD System with the Traditional AV System

This section presents the gains and drawbacks of the proposed system compared to the traditional AV system.

As we discussed earlier, traditional AVs should have a powerful processing capability to process sensor data within a short time. In-vehicle signal processing and storing burden can be minimized by the ELiD system, and more power and intensive processing can be done in the CL. This concept is the same as cloudification. A vehicle uses resources in the CL whenever it is necessary, without keeping a dedicated system to itself. This approach facilitates the efficient use of resources, such as GPUs and storage. Since the CL is equipped with sufficient resources, the processing is much faster (less than 100 ms) compared to existing AVs.

Reduction of in-vehicle processing will lead to improving the efficiency of AVs. It is necessary to have an excellent cooling mechanism in modern AVs. With the proposed system, manufacturers can reduce the power and mechanisms used to cool the cabin. Space utilization can be improved, and the weight of the vehicle will be reduced as the

Table 3.6. Simulation parameters

Number of ELiD base stations	1
Cell coverage	200 m
Number of frames per point	150
Centre frequency	5.9 GHz
Number of base station antennas	2
Doppler Model	'Jakes'
Power delay profile	'VehicularA'
Fading model	Rician
Wave form	OFDM
Bandwidth	5 Mhz
Number of subcarriers	300
vehicle density (UEs)	25 vehicles per km
Velocity of each vehicle	72 km/h

cooling system gets simplified. The shape of the vehicle is another critical factor that AV manufacturers should consider. In the proposed system, the vehicle structure will be the same as a non-AV. Furthermore, automobile manufacturers can be released from the signal processing related research, and they can focus more on the safety of the passenger.

Another significant benefit is the ability to minimize emergency accidents. The ELiD system is well aware of the upcoming events, and it can control the situation accordingly. Having real-time data beyond several hundred's of meters ahead is a great advantage in terms of safety that V2V protocols try to ensure. The system has the ability to succeed it without using V2V communication. The path planning will be much easier, and navigation will be much safer compared to the traditional AVs. In a vehicle-mounted LiDAR, the limited vision is a primary issue. Whatever the placement of the LiDAR in current AVs, there will be blind spots around the vehicle [37]. Sensors need to take the responsibility for those regions. The LiDAR placement of an AV is an unexplored field, unlike the placement of cameras [38]. One criterion to find an optimal placement is to minimize the blind spot or uncovered area. In the proposed architecture, the suggestion is to move/add a LiDAR with a bird's eye view, which is placed outside of the vehicle. The proposed approach can minimize the uncovered area one could obtain using a single LiDAR.

As existing AVs are equipped with more dedicated systems, the price is not affordable for the majority of the people. The ultimate solution should be an affordable AV. Otherwise, it will be a slow journey towards ITS. The reduction of expensive components from the AV will make it affordable to most of the people.

The system will remove duplicate data processing, which happens when each vehicle generates its map. In a highly congested road, two nearby vehicles will have approximately the same sensor data. Processing such data in two different systems is a waste of resources. The ELiD system can minimize the redundant data processing as summarized in Table 3.7 using an example scenario.

Table 3.7. Example scenario for reduction of redundant data processing ([3] ©2019 IEEE)

	Existing architecture	Proposed architecture
Vehicles per km	200 /km	200 /km
LiDAR density	200 /km	5 /km
Visible range	100's of meters	global map available

Traditional AVs use cameras to collect visible information like road signs, traffic light and fog lines. These structures can be eliminated since the stationary ELiD is well aware of the road infrastructure. It will reduce the cost of infrastructure maintenance.

The system is not only for AVs, but it can also communicate with V2I communication kit integrated non-AVs. Non-AVs can receive safety messages and alerts from the smart infrastructure and the driver can react accordingly. The proposed system will be able to manage the transition from manual driving to 100% autonomous driving smoothly.

All the vehicles navigate through a well-monitored system. Speed cameras and other monitoring equipment will not be useful anymore. All the speeds and road rule violations can be tracked even for non-AVs. It will lead to a transportation system with a proper discipline. A speeding driver can receive a warning first or a speed ticket immediately or later as an Email, as one wishes.

As additional advantages of the proposed system, it can significantly reduce the burden towards V2I and V2V communications. Making real-time data available to the road infrastructure using V2X is a difficult thing to be done due to uplink constraints. Collecting the data from the infrastructure with required accuracy reduces the burden towards communication standards. Stored data can be used by a third party to use in their applications like traffic monitoring. Third-party companies like telecommunication providers can design the required system, and they can operate it according to their policies and earn revenue with a one-time investment. Vehicle owners can make a subscription or pay rent for the service. Parallel to the smart city concept, this will be an ideal candidate for city transportation and factories of the future (FoF). The proposed system(Figure 3.11) has the ability to work as a standalone system, and in the meantime, it can play a supportive role with the traditional AV architecture.

3.4 Further Research Problems

According to the comments and feedback received from the colleagues and other reviewers, research problems needing further investigations are presented.

It is a known fact that the LiDAR is heavily dependent on the weather. When a LiDAR-system is mounted on a vehicle level to detect objects around the vehicle, performance and reliability reduction can be observed in raining and snowing conditions. By shifting the LiDAR-system from the vehicle level to an elevated infrastructure, the visibility under adverse weather conditions will reduce its performance further. Reliability of the sensor data under adverse weather conditions is an important research challenge that need more attention. The degradation of the LiDAR range as a function of rain intensity is analysed in [39]. Weather is a critical issue for the LiDAR regardless of the architecture. Ongoing research on LiDAR considers the effect of rain, fog and snow on its performance. Even the existing AVs will not become a reality without a solution to this issue. Under this situation, the system should handover the control to a human driver, which implies that the autonomy level 5 is an unreachable task without finding a solution for the weather effect on sensors.

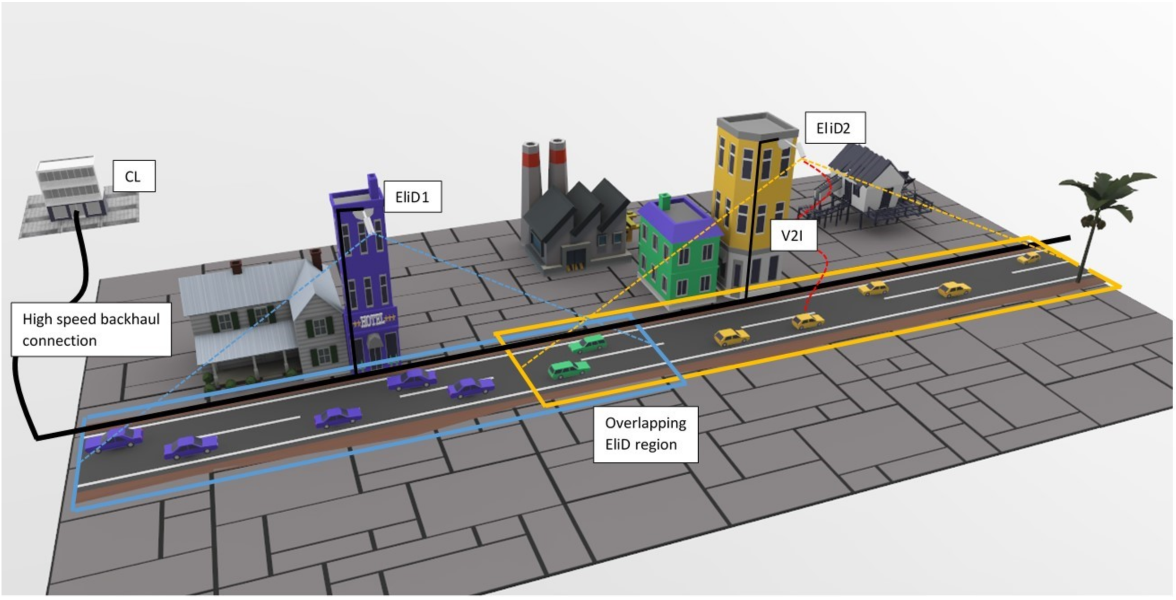

Figure 3.11. Graphical representation of the ELiD system ([3] ©2019 IEEE).

Advanced vehicle systems are mostly equipped with sophisticated security mechanisms. The data traffic within the vehicle usually are encrypted and renewed continuously with a new encryption key to avoid a single point attack. Manipulation or hacking a single module will affect a set of vehicles unless there is a robust cybersecurity mechanism. One possible solution to minimise the threat is to distribute the responsibilities of the CL, as discussed earlier. Vulnerability in the fronthaul is higher compared to the backhaul. In the fronthaul, the security mechanism should guarantee data confidentiality, integrity and availability. A software-based security architecture designed to protect V2I applications is presented in [40]. There is a lot of research going on to secure the V2I link.

The generation of collaborative maps in CL is another research problem. Collecting maps efficiently by removing redundancies and adding supportive data collected from the vehicles to generate a highly accurate global map is a difficult task. In the proposed system, we have used a commercially announced LiDAR where most of the encountered problems can be minimised with an application-specific LiDAR.

3.4.1 Other Applications

The proposed system can be used for many applications, not only for autonomous driving in an urban area. Other possible applications are described in this section.

Automation of the factories which have robots and AVs is one possibility (Figure 3.12). As self-driving cars are becoming popular in the streets, self-driving vehicles will come in to play on factory floors. A study carried out by PwC and Manufacturing institute in 2018 mentions that 9% of the manufacturers use semi-autonomous or AVs for their day to day operations. They expect this percentage to climb by 20% within the next three years [41]. Automated vehicles, such as shuttles and conveyors, have been in factory floors for several decades. The main objective is to reduce the human intervention from factory floors which will lead to an efficient and errorless flow of the process for a low cost. Amazon and BMW group are some of the leading companies who have already equipped their factory floors, with automated vehicles. As there are many mobile components on a factory floor, most of those can be navigated using the vision obtained from outside. As an application, this is less challenging compared to the autonomous navigation in an urban area. A factory floor is a well-controlled area with definite boundaries. This will minimize the complexity of the system.

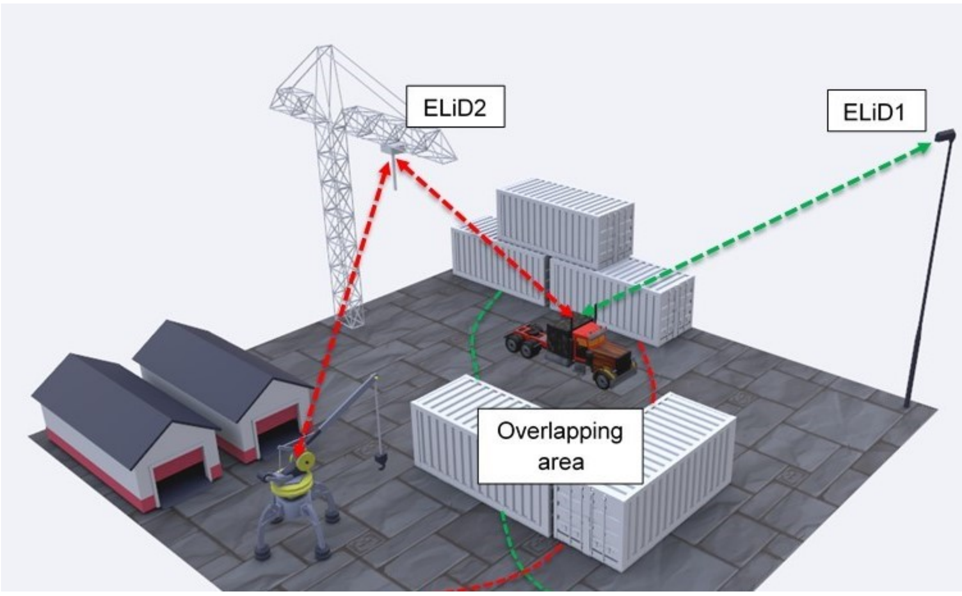

Figure 3.12. ELiD system for a factory floor.

Harbour automation is another application with a huge potential (Figure 3.13). Automated arrival and departure of ships and automation of cargo handling can be done using the proposed system. Mounted modules will cover the whole sea that belongs to the port. Here the module can be an ELiD or an Elevated camera (ECam). For a highly active port, available parking space can manage effectively with this kind of system. AVs can take control of cargo handling activities. The storage capability can be maximized with the proposed system.

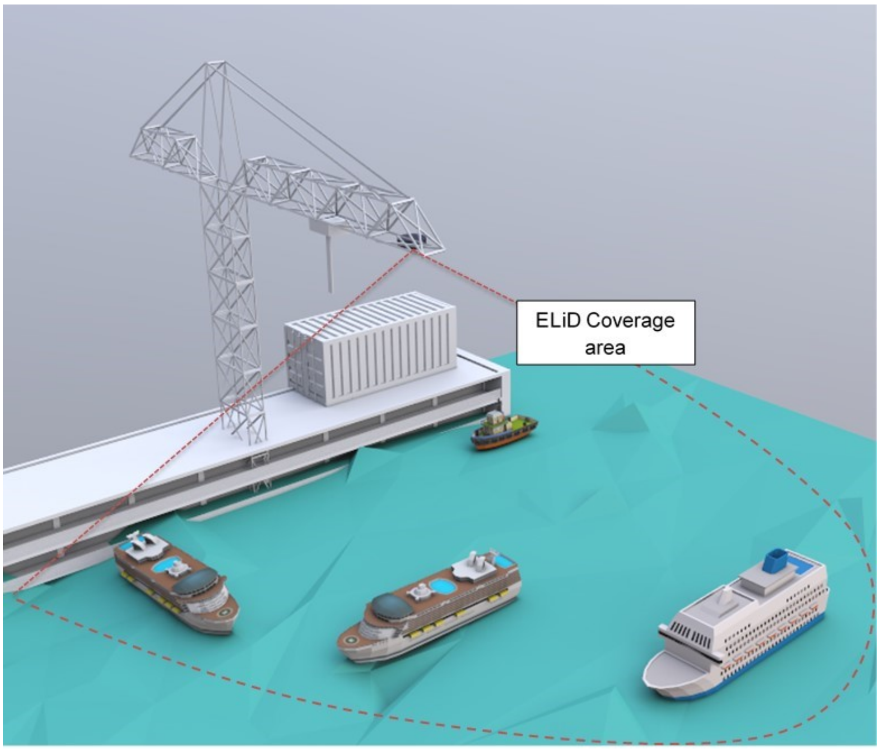

Figure 3.13. ELiD system for a harbour.

4 RESOURCE ALLOCATION FOR AN ELID SYSTEM IN A FACTORY FLOOR

In the past, robots in factories navigated by the aid of magnetic strips on the floor. With the development of advanced sensing technologies and the advent of AI, vehicles are configured to scan the environment. Decisions are taken based on their observations. Sensing technologies like radars, LiDARs and camera, collaboratively capture situation awareness data to make a floor plan around the vehicle to navigate without a collision. A set of on-board sensors will take care of vision as in modern AVs [42]. In recent years, wireless communication became a key enabler for factory automation [43].

Until now, all generations of cellular systems (2G, 3G, 4G) were focused to improve the data rates significantly compared to the previous generation. As the next-generation cellular system, 5G is playing a different role compared to the previous generations. As it focuses on broadband services with higher data rates, URLLC and M2M communications are two additional and main services concentrated by 5G. Generally, URLLC services require reliability higher than 10^{-5} with the end to end latency less than 1 ms [44]. Some mission-critical applications, like factory automation, may require reliability higher than 10^{-9} in terms of decoder error probability [45]. These facts show that industrial automation also requires extremely high reliability and low latency as in AVs in the road infrastructure. In a factory, there are low latency applications as well as reliable and secure applications. Driverless autonomous transportation systems are categorized under reliable and secure applications [46]. As mentioned before, reliability, latency and throughput are three key performance indicators of a communication system [47]. Figure 4.1 presents the variation of parameters with each other [48]. According to that, high reliability and low latency can be achieved when the throughput is minimal.

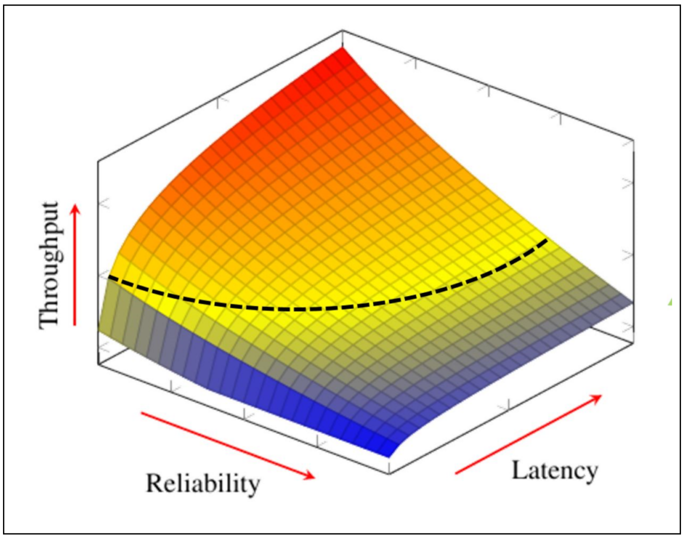

Figure 4.1. Tradeoffs among latency, reliability and throughput.

Autonomous navigation in a factory floor can be considered as one use cases for the ELiD system proposed in chapter 3. A factory floor with an ELiD system which facilitates autonomous driving within the factory is considered in this chapter. Section 4.1 discusses short packet communication, which is a key enabler of low latency communications to create the necessary background required for the problem.

4.1 Low Latency with Short Packet Transmissions

Various delay sources ultimately contribute to the total latency of a downlink communication [49]

$$L = d_Q + d_{ELiD} + d_{FA} + d_{Tx} + d_v \quad (6)$$

where, d_{ELiD}, d_v are processing delays of ELiD and vehicle, respectively. Both delays can be considered as constants from the communication point of view. d_Q, d_{FA} are queuing delay and frame alignment delay. In this chapter, the main focus is on d_{Tx}, which represents the transmission delay or transmission time interval (TTI) needed to transmit the packet. Even though air interface latency is only one latency component, it is mandatory to reduce the latency to make URLLC possible. Short packet transmission is one key idea behind URLLC. Generally, the packet size is very low (20 bytes) in URLLC services. Short packets can reduce above-mentioned delay components by a significant margin, and thus making efficient use of resources. As short packets were introduced, some adjustments were made for the existing principles in information theory.

As the packet length increases, thermal noise at transceivers and channel distortion will be equalised as a result of the law of large numbers. For a short packet length such equalisation becomes marginal. Another difference is that the percentage of symbols or bits required for the metadata (control information about the packet) is comparatively high compared to the large packets. As a result, the efficiency of transmissions will degrade. These are two main shortcomings of short packet transmissions [50].

The mapping between information payload and transmitted signals over the channel is defined as channel code. Receiver responsibility is to recover the transmitted information with low probability of error using the distorted received signal. Information theory states that as the packet length (or the number of channel uses required to transmit the information payload) tends to a large number, there exists a channel code which can reconstruct original information at receiver with a small probability of error [51]. Figure 4.2 elaborates the conversion of information bits to the transmitted symbols at the transmitter[50].

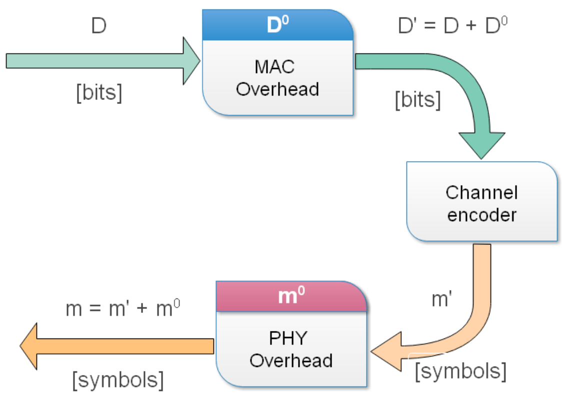

Figure 4.2. Packet generation as a block diagram.

Figure 4.2 shows the translation of D information bits that should be sent to the receiver. D^0 bits are added by the medium access control (MAC) protocol to the original information bits to make a total of D' bits. After that the channel encoder is translating

$D^{'}$ bits to $m^{'}$ symbols. $m^{'}$ more symbols will be added by the physical layer as its overhead, and it will result in a total of m symbols or channel uses to transmit D information bits.

In most of the communication systems $D^0 << D$ and $m^0 << m^{'}$. The ratio

$$R = \frac{D}{m} \tag{7}$$

is known as the rate, number of information bits per complex symbol with a dimension of bits per second per bandwidth [50]. The famous Shannon's capacity equation gives the maximum rate that the transmitter and receiver pair can achieve,

$$R = log_2\Big(1 + \gamma\Big) \tag{8}$$

where γ is the SNR at the receiver. As the block length is restricted to a finite number in the short packet transmission, the possibility of making an error in the decoder is no longer negligible. So, the maximum achievable rate for short block lengths becomes a function of decoder error probability (ϵ) and the short block length (m). Based on the Polyanskiy's approximation for the short block length [52], the maximum coding rate can be approximated as

$$R(m, \epsilon) \approx \left[\log_2(1+\gamma) - \sqrt{\frac{v}{m}} \frac{Q^{-1}(\epsilon)}{ln(2)} \right] \tag{9}$$

where v is channel dispersion, which is a function of SNR.

$$v = 1 - \frac{1}{(1+\gamma)^2} \tag{10}$$

$Q^{-1}(\epsilon)$ is the inverse function of the general Q-function.

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{y^2}{2}} dy \tag{11}$$

The second term in the right-hand side of (9) is a penalty given for the short block length. It is clear that as m goes to infinity, (9) reduces to (8).

4.2 System Model and Problem Formulation

From the basics we discussed earlier in this chapter, the system model and problem formulation are presented in this section. We consider a factory floor environment where multiple AVs perform their responsible tasks while navigating. As we discussed in Chapter 3, the ELiD module is mounted at a high elevation with bird's eye view. In this system, we consider a single ELiD module in the ELiD system to facilitate the autonomous navigation in the factory floor. Even though communication is bidirectional, we focus only on the downlink communication in this problem.

In the system, the ELiD module is responsible for establishing URLLC links with the set of AVs V where |V| is equal to n. The ELiD should communicate periodically with vehicles to steer those safely to the required destinations. All the vehicles are treated equally, and they require similar kind of information (steering angle, acceleration) for navigation. The CL generates the required information and sends to the ELiD for the transmission. The ELiD transmits the information as small data packets to guarantee the required latency. The transmission should be completed within time t_{max} to satisfy URLLC conditions. Symbol time (t_{sym}) decides the total number of symbols (M) that can be transmitted within the transmission time

$$M = \frac{t_{max}}{t_{sym}} \tag{12}$$

The system bandwidth of such a system can be found as

$$B = \frac{1}{t_{sym}} \tag{13}$$

Let us consider that all the vehicles require a packet with D bits periodically for navigation purposes. All bits should be transmitted within M symbols and all the vehicles should be served within M symbols. If D bits required for the i^{th} vehicle ($i \in V$) are distributed among m_i symbols, approximated rate for the i^{th} vehicle at the ELiD transmitter (channel state information at transmitter is assumed to be known) can be expressed by combining (7) and (9) as [45]

$$\frac{D}{m_i} = \left[\log_2(1+\gamma_i) - \sqrt{\frac{v}{m_i}} \frac{Q^{-1}(\epsilon_i)}{ln(2)} \right] \tag{14}$$

where γ_i and ϵ_i represent approximated SNR and decoder error probability at the receiver of the i^{th} vehicle. To make communication reliable, SNR should be high enough. According to (10), we can claim that v tends to 1 in high SNR regime. We consider an orthogonal multiple access technique to mitigate interference. The received signal at the i^{th} vehicle can be expressed as

$$y_i = \sqrt{p_i} h_i x_i + w_i \tag{15}$$

where p_i is the allocated power, h_i is the channel and x_i is transmitted signal to the i^{th} vehicle. w_i is zero mean white Gaussian noise (AWGN) with variance σ_i^2. A graphical view of the system model is shown in Figure 4.3.

The approximated SNR at the receiver of the i^{th} vehicle is

$$\gamma_i = \frac{p_i |h_i|^2}{\sigma_i^2} \tag{16}$$

Using (14) and (16),

$$\begin{aligned} \epsilon_i &= Q\left[ln(2)\sqrt{m_i}\Big(\log_2(1+\frac{p_i|h_i|^2}{\sigma_i^2}) - \frac{D}{m_i}\Big) \right] \\ &= Q\Big[g(\gamma_i, m_i, D) \Big] \end{aligned} \tag{17}$$

This shows that the decoder error probability is a function of SNR, block length and packet size. Since there are n vehicles in the system, let us define $\boldsymbol{\epsilon} = [\epsilon_1, \epsilon_2, .., \epsilon_n]^T$,$\boldsymbol{\sigma} = [\sigma_1, \sigma_2, .., \sigma_n]^T$, $\boldsymbol{P} = [p_1, p_2, .., p_n]^T$ and $\boldsymbol{M} = [m_1, m_2, .., m_n]^T$. In order to guarantee system reliability, all n vehicles in the system should have a minimum decoder error probability. The objective function of the resource allocation problem can be expressed as

$$\min_{\forall p_i, m_i} \left(\max_{\forall i \in V} \epsilon_i \right) \tag{18}$$

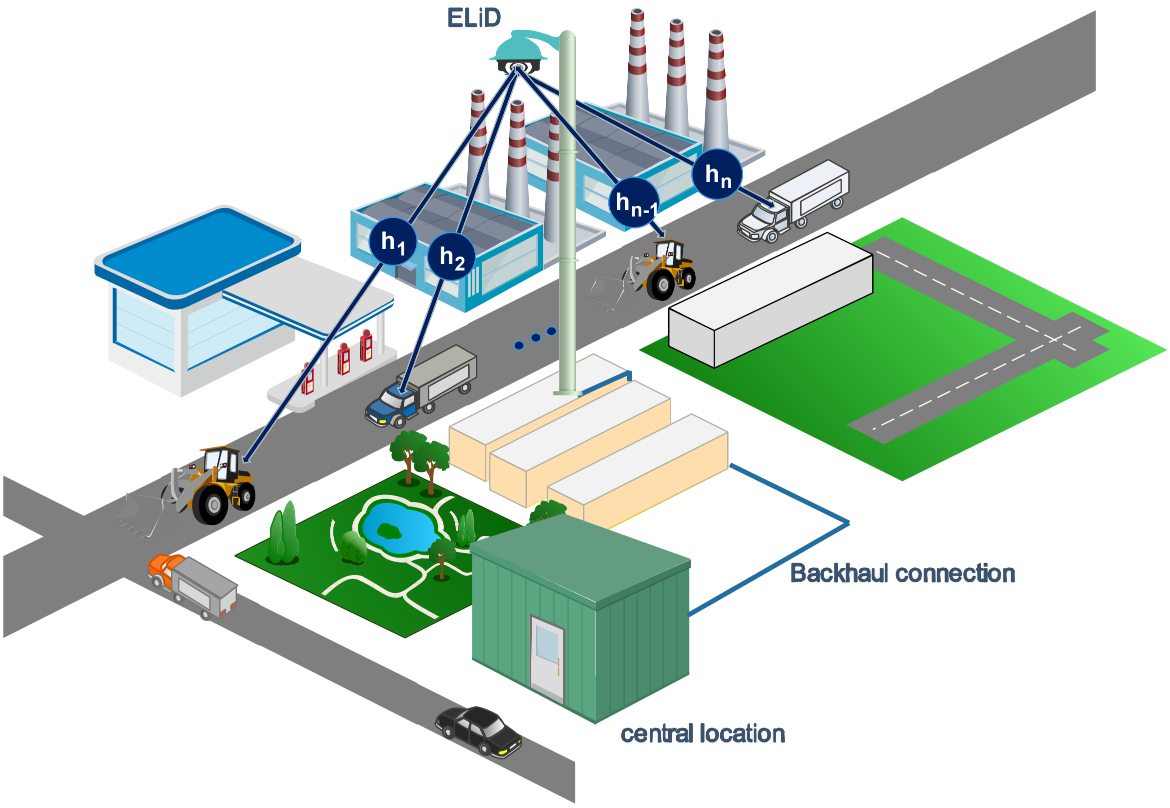

Figure 4.3. ELiD system facilitated autonomous navigation on a factory floor.

Since Q-function is a decreasing function, (18) can be reformulated as

$$\max_{\forall p_i, m_i} \left(\min_{\forall i \in V} g(\gamma_i, m_i, D) \right) \tag{19}$$

This formulation will be able to maximize the reliability of the system by minimizing the maximum decoder error probability of the vehicle experiencing it. Consider the infimum of $g(\gamma_i, m_i, D)$ $\forall i \in V$ as $-s$. A convex optimization problem can be formulated as

$$\min s \tag{20a}$$

$$\text{s.t}: \quad ln(2)Dm_i^{-1/2} - ln(1 + \frac{p_i|h_i|^2}{\sigma_i^2})m_i^{1/2} - s \leq 0, \quad \forall i \in V \tag{20b}$$

$$\|\boldsymbol{M}\|_1 \leq M \tag{20c}$$

$$\boldsymbol{P}^T\boldsymbol{M} \leq E_{tot} \tag{20d}$$

$$m_i \in \mathbb{Z} \quad \forall i \in V \tag{20e}$$

In the above formulation, constraint (20e) should be satisfied to meet the required reliability of communication for all vehicles. (20c) represents the latency constraint where the sum of block lengths should be less or equal to the total number of channel uses available in the system. Constraint (20d) presents the total energy constraint of the ELiD system. To reduce the search complexity and to avoid infeasible solutions, lower and upper bounds for m_i are defined. The minimum m_i satisfying the following equation is the lower bound (m_i^{lb}) of m_i [45].

$$h_i E_{tot} > m_i(2^{D/m_i} - 1) \tag{21}$$

According to constraint (20d) and (21), upper bound of m_i can be calculated as

$$m_i^{ub} = M - \sum_{\forall j \in V/i} m_j^{lb} \tag{22}$$

The feasible set for m_i can be found as [m_i^{lb},m_i^{ub}].

Algorithm 1 Maximum decoder error probability minimization of the ELiD system

```
Input: n,h,σ, D, M, E_tot
Output: P*, M*,max_error
for n do
    calculate m_i^lb and m_i^ub
    set m_i to random integer m_ik in [m_i^lb, m_i^ub]
end
M_k = [m_1k, m_2k,.,m_nk]
while True do
    minimize s for constant M_k
    s_1 = s and P = P_k
    minimize s for constant P_k
    s_2 = s and M = M_k
    if abs(s_1-s_2)< δ then
        max_error = s
        P* = P_k
        M* = M_k
        break
    end
end
```

The number of vehicles in the system, channel matrix, noise power matrix, number of information bits to be transmitted, the total number of channel uses available and the total energy of the ELiD system are inputs to the algorithm. Outputs are optimum user-specific powers, block lengths and the corresponding minimized-maximum decoder error probability of the system. According to (21) and (22), set $\boldsymbol{M}$ to a constant vector within the feasible range and calculate the minimum s for variable $\boldsymbol{P}$. As the next step, the minimization of s is carried out for a constant $\boldsymbol{P}$ (Optimal $\boldsymbol{P}$ from the previous stage) by setting $\boldsymbol{M}$ as a variable. If the convergence of s in both stages is low than a threshold, it can be considered as the optimal s. Otherwise, the optimization is repeated alternately until s converges to a minimum value. The next section contains the obtained results, summary and justifications.

4.3 Simulation Results

This section has provided simulation results to back up the viability of the infrastructure based communication architecture. In the simulation setup, we change the vehicle density (number of vehicles served by the ELiD) and minimize the maximum decoder error probability of the system by choosing an optimal resource allocation and user-specific power allocation. Our objective is to evaluate the performance of the system with varying vehicle density, block length and packet size. Simulation parameters are summarized in Table 4.1.

Table 4.1. Simulation parameters

Number of ELiD base stations	1
Cell radius	198.5 m
Height of ELiD	33 m
Number of vehicles (n)	2 to 12
System bandwidth	1 MHz
Noise power spectral density	-114 dBm/Hz
Path loss model	$36.7\log_{10}(d)dB$
Total Energy of the system (E_{tot})	0.4 kJ
Threshold(δ)	1×10^{-7}
Fading model	Rician

For both simulations, E_{tot} and noise power spectral density are chosen such that the receiver SNR is less than 10 dB for all the vehicles. The rician model is chosen over other fading models due to the dominant LOS component guaranteed by the ELiD system. Simulations were carried out for multiple channel realizations, and the average maximum decoder error probability of the system is considered in the simulation results.

First, we evaluate the impact of the block length by varying the total number of available symbols in the system. The resulting graph is shown in Figure 4.4. It demonstrates the performance of the vehicle, which has the maximum decoder error probability in the system.

We choose M to be a value less than 1000 so that it will satisfy the transmission delay of 1 ms. As we set system bandwidth (Table 4.1), the total transmission delay becomes $M\mu$s. The number of information bits or the packet size is set to 100 bits. According to Figure 4.4, the summary of best performing configurations for each vehicle density is shown in Table 4.2.

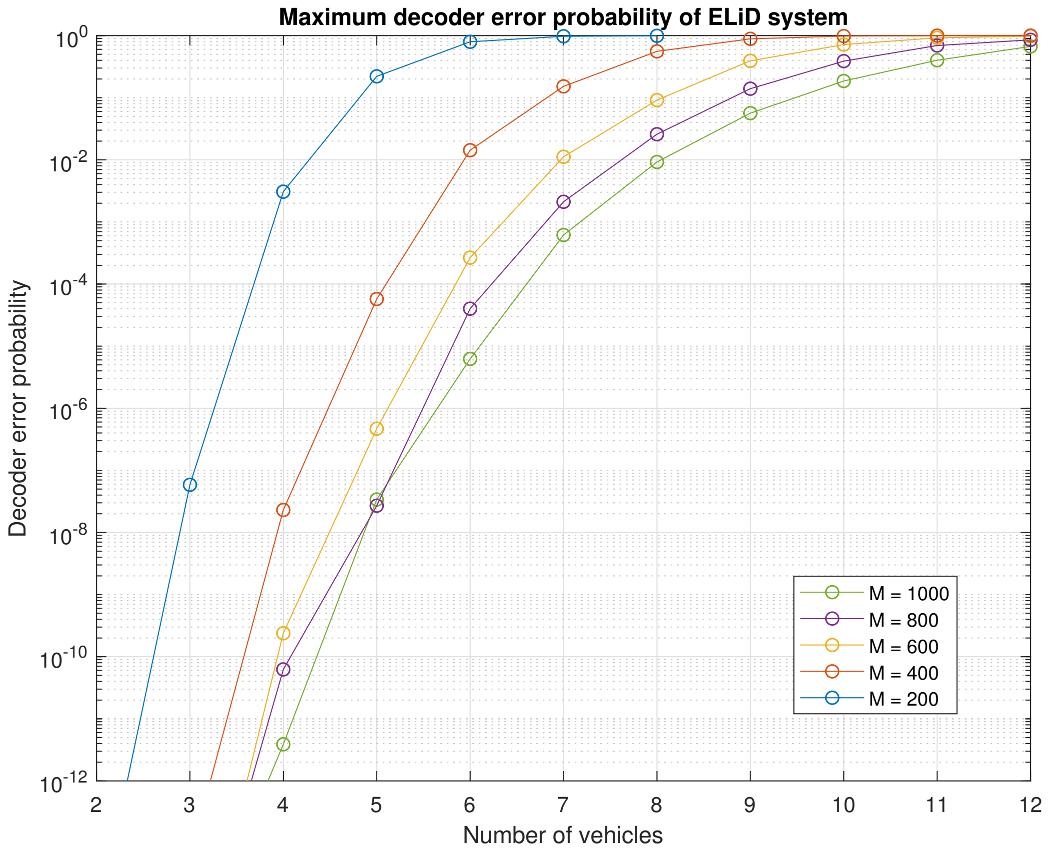

Figure 4.4. Maximum decoder error probability against the number of vehicles in the ELiD system with varying channel uses (D = 100 bits).

Table 4.2. Summary of Figure 4.4

Number of vehicles	2	3	4	5	6	7-12
Decoder error probability	$<10^{-9}$	$<10^{-9}$	$<10^{-9}$	2.7×10^{-8}	6.2×10^{-6}	$>10^{-5}$
Latency (ms)	0.2	0.4	0.6	0.8	1	1

According to the results, the lowest packet error probability of the system increase as the vehicle density increase. The packet error probability can be reduced by increasing the block length. It will eventually increase end to end latency for a given number of serving vehicles. The curves show that the ELiD will able to handle up to four vehicles with a reliability higher than 10^{-9} and latency less than 1ms. As the number of vehicles increases beyond 6, the system fails to deliver the required reliability under 1 ms latency for a short packet with 100 bits.

As the next step, we fix latency to be 1ms by setting M to 1000 and evaluate the rate for the vehicle having the maximum decoder error probability. The resulting graph is shown in Figure 4.5.

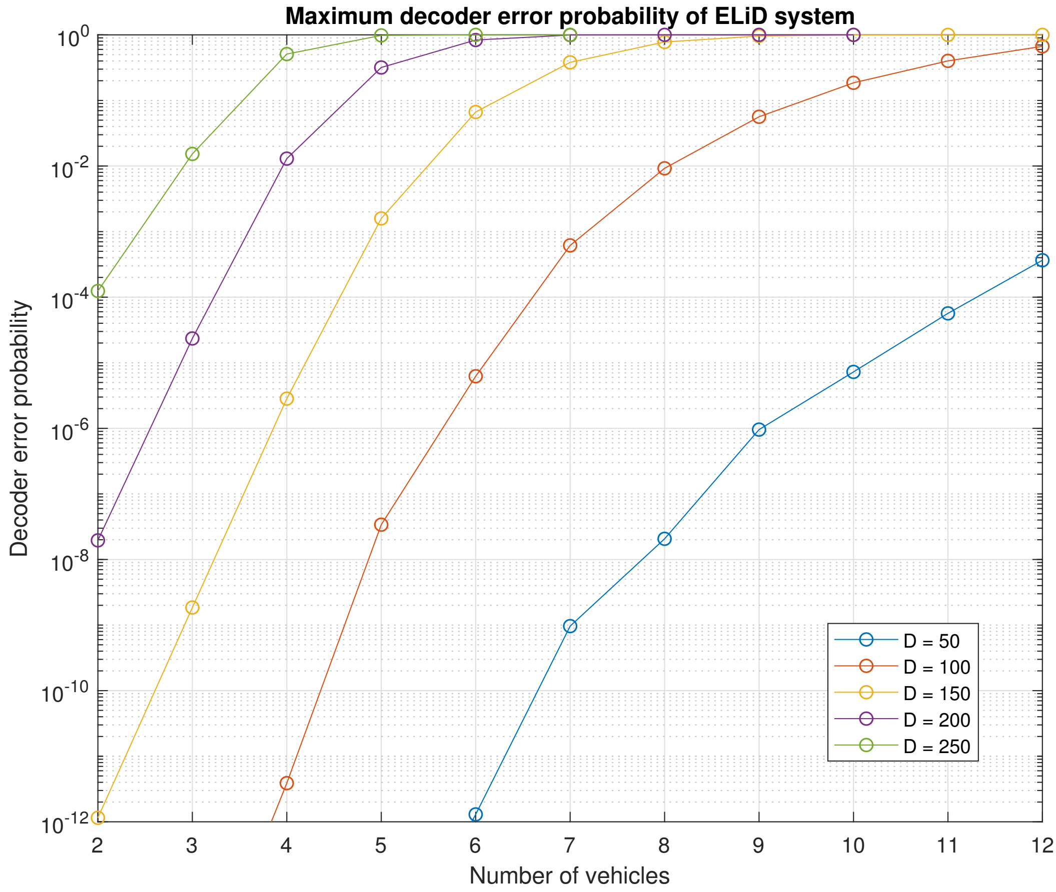

Figure 4.5. Maximum decoder error probability against the number of vehicles in the ELiD system with varying information bits (M = 1000 symbols).

We have considered the variation of packet size from 50 bits to 250 bits (generally the URLLC packet size is roughly 20 bytes or 160 bits). Using (7), we have calculated the optimal throughput and summary of the best performing configurations for each vehicle density according to Figure 4.5 (Table 4.3).

The resulting plots follow the same trend as in the first simulation and the reliability can be improved by reducing the information packet size for a given number of served vehicles. Smaller packets will lead to a lower packet error probability. At the same time it will reduce the throughput of the vehicle, which is experiencing the lowest decoder error probability in the system. According to Table 4.3, if the number of vehicles served by the ELiD system is less than 5, it is possible to maintain URLLC links with all the vehicles with the throughput higher than 100kbps while satisfying all URLLC constraints. If the number of served vehicles is greater than 10, the system fails to deliver the required reliability for the given set of parameters.

Table 4.3. Summary of Figure 4.5

Number of vehicles	2	3	4	5	6
Decoder error probability	$<10^{-9}$	$<10^{-9}$	$<10^{-9}$	$<10^{-9}$	$<10^{-9}$
Throughput (kbps)	150	100	100	50	50
Number of vehicles	7	8	9	10	11-12
Decoder error probability	$<10^{-9}$	$<2 \times 10^{-8}$	9.5×10^{-7}	7.2×10^{-6}	$>10^{-5}$
Throughput (kbps)	50	50	50	50	50

4.4 Discussion

Simulations prove that the proposed system is a communication-wise feasible candidate to enable remote driving on a factory floor. AV density on a factory floor is much less compared to the AV density in roadways so that simulations are carried out for low vehicle densities. Speeds of the vehicles are much lower compared to those of the road infrastructure, and it will improve the accuracy of the proposed system from sensing point of view.

In the optimization algorithm, the minimization of the maximum decoder error probability is carried out by fixing $\boldsymbol{M}$ and $\boldsymbol{P}$ alternatively, until the error converges to a threshold value. The alternating optimizing approach leads to a sub-optimal solution. We swapped the fixing order of $\boldsymbol{M}$ and $\boldsymbol{P}$. Then the same set of simulations was carried out using the modified algorithm. The resulting optimal values were better in the previous case. As the block length of a user is a positive integer, the round off operation is carried out in each iteration. It might cause a negligible error in the resulting optimal value. Since path loss is dominant with respect to link budget in most of the cases, cell edge vehicles experience the highest packet error probability of the system among all other vehicles in most of the cases. Simulations guarantee that all other vehicles in the system will experience a service better than the shown results.

Furthermore, the calculation of the lower bound and the upper bound for all m reduces the searching complexity of the algorithm. Moreover, lower bound of m guarantees that the achievable rate does not exceed Shannon's rate. It prevents the solution being infeasible. The upper bound constraints the total available resources or symbols, in other words, maximum transmission latency. The algorithm reaches the optimal solution within three iterations regardless of the number of vehicles in the system. As the number of vehicles in the system decreases, the number of required iterations decrease.

This work analytically proves the viability of the system to maintain multiple URLLC links with AVs on a factory floor. The system has the ability to handle multiple vehicles simultaneously with a transmission latency less than 1ms and the reliability greater than 10^{-5} in terms of packet error probability. Achieving such error probability using Monte Carlo simulations is difficult due to lack of processing capabilities. This result can be verified using a link-level simulation for decoder error probabilities less than 10^{-6} as the next step. In the system, we have considered an orthogonal resource allocation for vehicles in order to mitigate interference for betterment of the performance. The performance of the system can be improved using a multi-carrier system with more resources.

5 CONCLUSION AND FUTURE WORK

5.1 Summary and Conclusion

It is a known fact that V2X communication is a key enabler for fully AVs. So far it has become a trending research area in wireless communications. Almost all of these efforts are focusing on collecting situational awareness data from outside and share the data with the vehicles to improve the reliability of the decisions that AV makes. In this work, the signal processing burden on vehicles due to the existing stand-alone AVs has been discussed. It is an obvious fact that the burden on signal processing will increase since every bit of information is processed within the vehicle. The other option would be to offload the collected information from the vehicle to the infrastructure to reduce in-vehicle processing. However, with the V2X technologies developed so far, it is impossible to support the required Gigabit range uplink data rates with the required reliability and latency. Therefore, the objective of this work was to provide a feasible solution by addressing all these issues.

The proposed system collects situational awareness data from the infrastructure and process the collected data in a centralized location. Only the information required for navigation will be sent back to vehicles. The system can be deployed using the commercially available LiDARs. This work proved the sensing feasibility, using Velarray LiDAR announced by Velodyne Lidar. One ELiD module requires two LiDARs to cover a responsible road section. The ELiD should be mounted at the height of 33 meters above the ground level, and it can cover a road section of 397 meters. A set of link-level simulations were carried out to evaluate the performance of the system using the LTE framework. We have presented the additional advantages of the system over the traditional architecture. After that, we have been discussed the other use cases where the system can be implemented.

The factory floor automation scenario has been considered in Chapter 4. The ELiD needs multiple URLLC links to communicate with the moving vehicles. A convex optimization problem has been formulated for the orthogonal resource allocation among vehicles. Each vehicle requires a packet with a constant size, and all the vehicles should be served within 1ms transmission latency. In the first simulation, the system can achieve a decoder error probability less than 10^{-5}, if the number of serving vehicles are less than 7. A latency less than 1ms has been achieved in all the cases. It shows that 100bits can be sent with the required low decoder error probability and latency constraints for all the cases. As the next step, we fixed the latency to be 1ms for all cases, and evaluated the performance by varying the number of vehicles in the system. The throughput for each vehicle decrease as the number of vehicles increase. The decoder error probability of the system decrease below 10^{-5} as the number of vehicles increase beyond 11. The proposed system achieves the required key performance indicator values for low vehicle densities.

Finally, we can claim that the proposed infrastructure-based communication architecture is feasible from sensing point of view as well as from the communication viewpoint.

5.2 Future Work

As we have mentioned earlier, the harbour automation is another use case that can be facilitated by the proposed architecture. One work package of the project 5G-Viima is focusing on novel technical solutions that can enable autonomous driving or self-navigating robots. It will be an excellent platform to test the proposed architecture.

The mathematical modelling of the system is still at its initial phase. The system should be modelled with more realistic channel models, and the simulations should be done extensively to analyse the performance of the communication system. The proposed system also can provide solutions for the indoor and outdoor positioning-related research. For example, the 5G positioning is an open research problem so far due to highly directive antennas with mm-Waves in a highly dynamic environment. Such problems can be considered as a second phase research problems which can be addressed on top of the proposed ELiD architecture.

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